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TASK FINAL REPORT

on

FEASIBILITY OF SATELLITE INTERFEROMETRY FOR SURVEILLANCE, NAVIGATION, AND TRAFFIC CONTROL

(Report No. BCL-OA-TFR-76-2)

by

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TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

LIST OF TABLES

LIST OF TABLES
(Continued)

LIST OF FIGURES

FOREWORD

This investigation was performed by Battelle's Columbus Laboratories (BCL) for the Office of Applications, Communications Programs of the National Aeronautics and Space Administration (NASA). It was performed as Task 3 under BCL's contract with NASA's Office of Applications for the project entitled "NASA Application Studies - New Initiatives" (Contract No. NASw-2800). Mr. Forrest Waller serves as the NASA Technical Monitor for this project and Dr. A. C. Robinson acts as Project Manager for BCL. Mr. Paul McCeney was NASA Technical Monitor for this task effort for which Mr. A. G. Mourad served as BCL Task Manager.

The effort, originally called for in the Work Statement, was a feasibility study of an interferometer system for navigation and spacecraft attitude control. Earlier investigations conducted by NASA/Goddard Space Flight Center (GSFC) and others in the area of spacecraft attitude control were analyzed and evaluated by BCL and it was concluded that they provided sufficient data to demonstrate the interferometer capability for attitude control. Consequently, BCL recommended, and NASA agreed, that the emphasis for the remainder of the program be shifted and that a preliminary survey be conducted to learn the various applications and requirements of potential users in Government and industry for the interferometer system. Mr. Mourad conducted most of the interviews and compiled and interpreted the data obtained from them. On a number of occasions Mr. McCeney participated in the interviews, and his cooperation, interest, and helpful suggestions during the course of the study are greatly appreciated. The excellent cooperation of the interviewees and their organizations (see Appendix for listing) is also gratefully acknowledged. Other analyses and evaluations performed during this investigation and the BCL personnel principally responsible for their performance are: Software System Analysis, Dr. S. Gopalapillai; Hardware System Analysis, Mr. G. T. Ruck; Survey of Competitive Navigation Systems and Comparison with the Interferometer System, Dr. Gopalapillai and Mr. Mourad.

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by

S. Gopalapillai, G. T. Ruck, and A. G. Mourad

1.0 INTRODUCTION AND BACKGROUND

The two key elements that must be considered in the design of any system intended to perform surveillance, navigation, and traffic-control functions are position location and communication. Five basic types of systems are in use today (surface-based radio, celestial, self-contained inertial, acoustic, and satellite) which perform some or all of these functions, yet no single system has been developed that is capable of meeting the requirements of all users. Most investigators, however, agree that a satellite navigation system can be designed and built which will meet the requirements of most users.

Conceptually, addition of one-way communication from the craft or vehicle to a control center will result in surveillance capability. If the communication is two way, it will add traffic-control capability with the potential for a variety of other applications such as collision avoidance, search and rescue, data transfer, etc. At present, no operational system has all of these capabilities; however, many studies, including proof-of-concept demonstrations, have been conducted by various Government organizations. The DOD expects to have an operational navigation (position and velocity) system by 1984-86 for both military and civilian use. The DOT/FAA is involved in tests and experiments addressing technology and concepts applicable to aeronautical satellite communication and air-traffic-control systems while the DOC/MarAd is conducting similar experiments to develop maritime satellite communication and surveillance/navigation systems. A fully operational system, however, will be some time in the future.

A successful civilian navigation/communication system must include the following criteria:

(1) All-weather capability

(2) Continuous (or nearly so) positioning capability

(3) Global or almost global coverage

(4) Good accuracy in positioning

(5) Singularity in reference datum

(6) Dependability

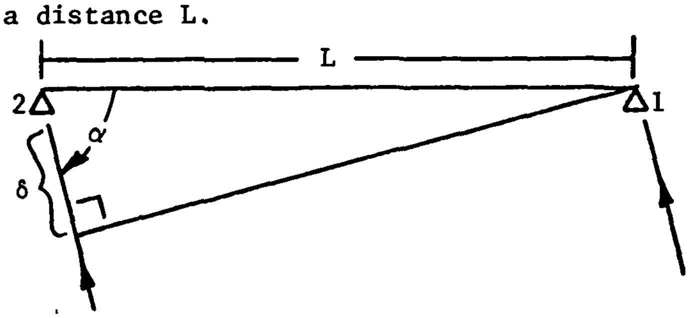
(7) Low cost to user.

The advantages of a satellite system for meeting the above criteria far exceed all other types of surface-based systems. Three basic types of data combinations have been generally considered for a global satellite position location system usable by air, sea, or land crafts: (1) distance or distance difference, (2) angles and distances, and (3) rate of change of distances. The interferometry system to be considered in this investigation is the angle-measurement type used either independently or in conjunction with distance measurements.

Before introducing the subsection which describes the objectives of the present investigation and the approach used in accomplishing them (Subsection 1.3) some additional background information has been provided in the following two subsections. The first of these, designed to assist the readers who may be unfamiliar with the concept represented by the satellite interferometry system, provides a brief discussion of the principles involved in such a system. The second reviews two major studies in which the feasibility of applying satellite interferometry techniques to spacecraft attitute control was investigated by NASA/GSFC and IBM for NASA. The organization of the remainder of the report is given in Subsection 1.4.

1.1 Principles of Satellite Interferometry

An interferometer is basically a receiving system which achieves high accuracy in the measurement of the angular position of a radiating source by the use of two or more antenna elements separated by a baseline many wavelengths in extent. This is demonstrated below, where a plane wave of wavelength λ is incident at an angle α relative to an interferometer consisting of two antenna elements separated by a distance L.



Assuming the phase of the received signal at antenna 1 is given by Φ_1 (any arbitrary value between 0 and 360°), the phase at antenna 2 is Φ_1 plus the additional phase shift introduced by the distance δ. This is given by $k_o\delta$ where k_o, the wave number for the incident field is $2\pi/\lambda_o$ and $\delta = L \cos\alpha$. The phase of the signal at antenna 2 then is $\Phi_2 = \Phi_1 + \frac{2\pi L}{\lambda_o} \cos\alpha$, and the phase difference between the two antennas is

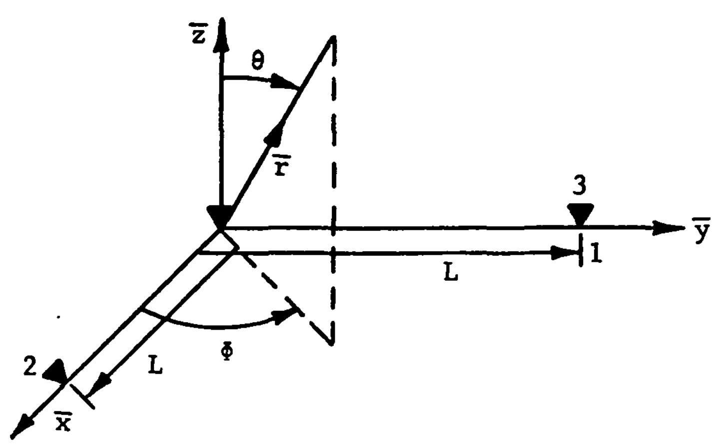
$$\gamma = \frac{2\pi L}{\lambda_o} \cos\alpha \quad .$$

For L/λ_o large, then many radians of phase difference can occur for small differences in α. In addition, since phase can only be measured modulo 2π, the same phase difference is observed for values of α such that

$$\alpha = \cos^{-1} \frac{\lambda_o}{L} \left(n + \frac{\gamma}{2\pi} \right), \; n = 1,2,3,\ldots$$

This results in an ambiguous angle determination if only two antenna elements are used.

The primary differences between various interferometer systems is in the manner in which the phase differences in the signals from the various antenna elements are measured and in the specific interferometer application. If employed on a spacecraft, there will obviously be differences between a system used with a low-orbit spacecraft and one used with a geostationary spacecraft. For a stabilized geostationary spacecraft, the spacecraft position and orientation can be relatively constant, thus the orientation in space of an interferometer baseline is fixed. Two orthogonal interferometer baselines can be formed by the use of three antennas placed as indicated below.



For this interferometer, the phase difference between antennas 1 and 2 (baseline 1) for radial vector $\bar{r}_1$, is

$$\gamma_{11} = \frac{2\pi L}{\lambda_o}(x \cdot \bar{r}_1) = \frac{2\pi L}{\lambda_o} \sin\theta \cos\Phi \quad , \tag{1-1}$$

while the phase difference between antennas 1 and 3 (baseline 2) for $\bar{r}_1$, is

$$\gamma_{21} = \frac{2\pi L}{\lambda_o}(\bar{y} \cdot \bar{r}_1) = \frac{2\pi L}{\lambda_o} \sin\theta \sin\Phi \quad . \tag{1-2}$$

If the radial vectors $\bar{r}_1$ and $\bar{r}_2$ to two ground stations are known, this defines four angles θ_1, θ_2, Φ_1, and Φ_2 sufficient to establish the spacecraft orientation. If three radius vectors to the ground are defined, then six angles are determined, enough to establish both the satellite attitude and position. Once the attitude is established, the phase-difference measurements to a ground station of unknown position will define its position (latitude and longitude). Obviously a single baseline could also be used in conjunction with other sensors such as an Earth sensor or Polaris tracker to determine the spacecraft's attitude.

An interferometer-based navigation system requires both transmitting and receiving capabilities at both the spacecraft and the user ground station.

1.2 Past Interferometry Studies and Experiments

At least two major experiments involving the principles of satellite interferometry, as outlined above, have been conducted:

(1) The NASA/GSFC SAPPSAC (Spacecraft Attitude Precision Pointing and Slewing Adaptive Control) experiment (Isley, 1975a and 1975b; Isley and Endres, 1975a and 1975b).

(2) Interferometry Position Location Concept Studies conducted by IBM Corporation under contract to NASA: Feasibility (IBM, 1970a), Phase Recovery and Calibration (IBM, 1970b), Bench Test and Experiments (Tsitsera, et al., 1973).

A brief summary of these experiments and their results as described in the above-cited references are offered here as background information.

1.2.1 SAPPSAC Experiment

In this experiment, using the NASA ATS-6 geostationary satellite, the ground terminal performed the attitude determination and generated torque commands for attitude control. This experiment also included provisions for on-line determination of spacecraft position and velocity using two interferometer beacons and the Earth sensor. It should be noted that only one of the two orthogonal baselines was operational. A unified algorithm was employed in the ground controller to determine both three-axis attitude and spacecraft position using a combination of onboard sensors [Polaris tracker, Earth sensor, and two-channel interferometer with optional use of the YIRU (gyro)]. This sensor information is extracted by the controller from the normal telemetry stream.

A total of nine tests were performed demonstrating several capabilities including those in attitude hold, pointing, slewing, tracking (ground), interchangeability of sensors, and orbit determination (Isley and Endres, 1975a and b). Attitude excursions over 43 minutes were held to 0°.004 in pitch and roll, and 0°.016 yaw. Short periodic (5 minutes) excursions were held to 0°.002 in pitch and roll. The Z-axis (spacecraft) pointing was stabilized to 0°.007 in pitch and roll for 43 minutes. Reference, time-tagged ground tracks were followed with errors less than 0°.15 in latitude and longitude. The orbit was determined with a "confidence of about 9 km in the latitude and longitude and 2 km radially".

It must be pointed out that these numbers reflect the performance of the integrated sensors. Consequently, these results may be contaminated by large errors due to the horizon variation and/or sun-avoidance logic of the Earth sensor. The performance of a two-baseline interferometer is, therefore, anticipated to be better than that reflected in the results of the SAPPSAC experiment.

1.2.2 IBM Studies and Experiments

Under contract to NASA, IBM Federal Systems Division carried out a series of studies and experiments on an interferometer surveillance system. The interferometer system examined had two orthogonal baselines and was to be carried by a geostationary satellite which measured the positions of up to 15,000 meteorological balloons and relayed data measurements such as temperature, pressure, etc., at the rate of 10 bps to a central ground processing site. This system was to monitor the position of these balloons to a 1σ accuracy of 1 km.

The interferometer system examined consisted of crossed 75-m baselines operating at a frequency of 1.6 GHz providing 400 λ baselines. The balloon transmitters radiated 1 w through essentially omnidirectional antennas, and a receiver integration time of 10 seconds was used.

Analytical studies of interferometer error sources were conducted and the interferometer hardware was designed. Prototype hardware was built and bench tested. The bench tests resulted in an overall instrumentation error in the interferometer receiving hardware of $0^\circ.23$ (1σ).

As a part of this effort an extendable boom suitable for this application was designed and a 3.5-m scale model was constructed. Extensive analyses of the properties of this design were performed with respect to motion of the boom end due to thermal effects and vibration. Tests carried out on the 3.5-m scaled model in a thermal vacuum chamber verified the analytical predictions of boom behavior.

The positioning performance of the prototype hardware was determined using a three-channel interferometer by testing on a ground range in a two-dimensional configuration. A 100 λ baseline length was used in these tests to insure that multiple errors would not invalidate the measurements. Positions were measured on this range of 0.51 cm (0.2 in.) (1σ) and 0.68 cm (0.27 in.) maximum. This scales to accuracies of 0.74 km (1σ) and 1 km maximum for the 400 λ baseline interferometer in geostationary orbit.

1.3 Objective and Scope of Present Investigation

This investigation was originally undertaken to determine the feasibility of the interferometer system for position determination and spacecraft attitude control. A specific interferometer system, developed primarily for attitude control, that is currently mounted on-board the geostationary ATS-6 satellite was studied. Experiments which have been conducted with the ATS-6 interferometer system have demonstrated its ability to provide high-precision attitude control data (see Section 1.2). After a careful review and study of these and other essential experiments it was decided that the attitude control capability of the interferometer had been adequately examined and demonstrated and, by agreement with NASA, the emphasis of the remaining portion of this effort was shifted to an investigation and determination of other capabilities of the interferometer system and was to include recommendations of areas for further exploration with regard to hardware, new experiments, and potential user applications.

The approach to this investigation involved conducting systems analyses of interferometer hardware and software, surveys of competitive navigation systems and comparison of their capabilities with those of the interferometer system, and a preliminary survey of potential users to determine their particular applications and requirements for them.

1.4 Report Organization

The report of this investigation has been organized in the following manner: Section 2 provides a summary of the results obtained, conclusions drawn on the basis of these results, and suggested recommendations for future experiments and investigation. Section 3 contains the details of the software system analysis including the formulation of the mathematical model, the solution of the position-determination problem, and the effects of both random and systematic errors in the measurements, system parameters, and other associated parameters.

The hardware system analysis and results are given in Section 4. Various interferometer system concepts and system parameter selection are described following the examination of the various error sources inherent in the systems. The specifications, performance, and cost of the "strawman" system configurations are also detailed.

A survey of competitive navigation systems and a comparison with the interferometry system is presented in Section 5 and, finally, Section 6 discusses requirements and applications of prospective users of the interferometer system as determined from a limited preliminary survey.

In the following, notations used for equations are consistent within each section but not necessarily from one section to another. This should not create any problems since they are explained wherever they are introduced.

2.0 SUMMARY OF RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

2.1 Summary of Results

This investigation determined the feasibility of using a satellite-borne interferometry system for surveillance, navigation, and traffic-control applications. It comprised a two-part systems analysis (software and hardware); a survey of competitive navigation systems (both experimental and planned) and a comparison of their characteristics and capabilities with those of an interferometry system; and a limited survey of potential users to determine the variety of possible applications for the interferometry system and the requirements which it would have to meet. Five candidate or "strawman" interferometry systems for various applications and with various capabilities were configured (on a preliminary basis) and evaluated.

The principal advantages inherent in satellite interferometry, as pursued in this study, are:

(1) It achieves high accuracy in the measurement of the angular position of a radiating source.

(2) A single, suitably equipped geostationary satellite can provide regional coverage of the Earth (for example, most of the Atlantic Ocean and the continent of America) and three such satellites can provide global coverage between 70° north and south latitudes.

(3) Additional capabilities such as surveillance, traffic control, data collection/transfer can be made available with minimal equipment modification or cost increase since an interferometer-based navigation system will have both transmitting and receiving capabilities at the satellite as well as at the ground station.

(4) The same angular measurements used to obtain position fix can also provide information for attitude reference and/or control of the spacecraft.

On the basis of this study, it appears that interferometry in conjunction with a geostationary satellite has an inherent ability to provide both a means for navigation/position location and communication, and offers a very high potential for meeting a large number of user applications and requirements for navigation and related functions.

The specific results obtained in each of the four major parts of this study are summarized below. These are followed by the conclusions drawn on the basis of these results, and some recommendations for possible future efforts in this area.

2.1.1 Systems Analysis: Software

This analysis provides a mathematical formulation of the problem of the determination of position by means of a satellite-borne interferometry system. The interferometry system considered is mounted aboard a geostationary satellite and consists of a pair of baselines at right angles to each other with microwave receiving antennas at each of their ends. The phase difference between the signals received by the antennas at each end of a baseline from a ground-based microwave transmitter is a measure of the space angle between the baseline and the direction of the transmitter. Two such angles formed by the two baselines will define the direction of the transmitter with respect to a local coordinate system defined by the baselines. The space angle between the directions to two ground transmitters, is defined by these directions and is independent of the attitude of the local coordinate system relative to an Earth-fixed system. The relationship between this angle and the position of the satellite and the transmitting stations forms the basis for the mathematical model used in this analysis. This model also includes such systematic error model parameters as the nonorthogonality between the baselines and the biases in the phase-difference measurements.

The principal objective of the analysis was to investigate the effects of the various system parameters on position-location accuracy and to determine the values or characteristics of these parameters which will permit the achievement of optimum accuracy. The following parameters were considered:

(1) Ratio of the length of the baseline to the wavelength of the transmitted signal
(2) Precision of the phase-difference measurements
(3) Stability of the frequency of the transmitted signals
(4) Uncertainty in reference-station coordinates
(5) Error model parameters (nonorthogonality and biases in the phase-difference measurements)

(6) a priori estimates of the satellite position and their uncertainties

(7) a priori estimates of the unknown station position

(8) Geometry of the reference stations' configuration

(9) Position of the unknown station with respect to the satellite nadir point.

The approach to the analysis was to linearize the mathematical model to form a set of condition equations which were solved using the generalized Least-Squares technique. With this technique, observables of a heterogeneous nature, with different levels of precision, and any a priori information available on the unknown parameters, can be combined to obtain a set of optimum estimates for the parameters. Also, the use of Pope's technique (Pope, 1972) for the solution of a set of nonlinear condition equations enables the solution to converge more quickly to values corresponding to the minimum variance. Since actual data were not available to satisfy the data requirements for the system analysis planned here, it was necessary to rely on data simulated in as realistic a manner as possible and independent of the mathematical model used here in order that the formulas derived could be verified and validated.

This systems analysis revealed the following:

(1) The accuracy, σ_H, of determination of a station position is critically dependent on the baseline length, L, and on the magnitude of the random component, σ_γ, of the phase-difference measurement errors. This dependence can be formulated by simple mathematical rules ($\sigma_H \propto \frac{1}{L}$ and $\sigma_H \propto \sigma_\gamma$) so that interpolation or extrapolation can easily be performed as desired.

(2) The accuracy of determination of position is almost independent of any bias in the phase-difference measurement.

(3) The magnitude of errors known to be associated with the position of the reference stations and with the satellite ephemeris has negligible effect on the accuracy of position determination. This is also true of the effects of uncertainties inherent in the transmitted frequencies.

(4) Effective changes in the baseline lengths and the non-orthogonality parameter can be determined simultaneously with the unknown station position if three reference

stations are used. However, the effects of these parameters are negligible for baselines shorter than about 40 to 50 m, in which case two reference stations are sufficient.

(5) The accuracy of position determination deteriorates as the unknown station position is moved away from the satellite subpoint. This deterioration is marginal (<30 percent)* for positions up to about 30° to 35° and becomes quite significant beyond 35° to more than 100 percent at about 55°.

(6) For the technique used in this study to solve for the unknown station position and other parameters, the accuracy of the a priori estimates of the unknown station position is not critical in that such an estimate will be available to within about 1500 km.

(7) The satellite position cannot be determined accurately by the interferometry system above. Some type of a priori information on the satellite position is necessary for accurate determination of the ground station position. Satellite position to 10 km is sufficient to produce only a 5 percent error in the ground station location.

2.1.2 System Analysis: Hardware

In this analysis of interferometry hardware, a number of interferometer concepts were considered, potential hardware-related error sources were identified, and possible trade-offs between various system parameters were examined. Five candidate or "strawman" interferometer systems, based principally on the equipment requirements of potential users, were configured. These include systems for: (1) surveillance and data collection; (2) low-capability navigation (125 to 500-m accuracy), surveillance, and data transfer; (3) high-capability navigation (25 to 75-m accuracy), surveillance, and data transfer; (4) aerial navigation and air-traffic control with data transfer; and (5) "all-purpose", capable of providing surveillance, navigation, and data transfer with varying positional accuracy, depending upon user requirements. It should be noted that all of these systems are based on the use of a 50-m interferometer baseline on a geostationary spacecraft, although this study has also considered several other baseline lengths. The 1-m baseline of the ATS-6 does not provide sufficient accuracy for most of the applications considered in this study. The 50-m baseline length was selected

*The % is computed based on the accuracy at the subsatellite point as being best.

for the following reasons: booms with lengths of this order are planned for NASA's disaster warning satellite, which could provide a platform for an interferometer positioning system experiment; and such lengths should be readily attainable and would allow an interferometer system to compete effectively with other types of positioning and/or navigation systems with regard to performance. It has also been found that, contrary to what might be expected, the effects of thermal expansion or contraction and vibration are negligible for the various applications considered in this investigation.

Another system concept, the inverse interferometer which is quite different from the five conventional strawman systems was touched upon briefly in this investigation. In this system, as in the others, the spacecraft carries the interferometer antenna array, however, instead of receiving, a different frequency is transmitted from each antenna, all of which have been coherently derived from a common frequency source. On the ground, these frequencies are received and coherently translated to a common frequency for phase comparison and measurement. This system would have the advantages common to all systems in which the user requires only passive hardware: unlimited number of users, relatively low cost of equipment, and minimal frequency allocation requirements, since no transmitter is required. Disadvantages also exist; spacecraft attitude must be more precisely known, phase bias errors resulting from spacecraft hardware will not be compensated for, and a surveillance or data-transfer capability could not be provided.

The applications, accuracies, and costs of the five "strawman" systems are summarized in Table 2-1. These systems are believed to be representative of the current state of interferometer technology, however, experimental demonstration and verification is required and, of course, considerably more detailed system specifications must be defined for an operational interferometer system. In addition, the system costs and specifications for the spacecraft and central-site processing hardware need to be identified.

A brief review of the characteristics, hardware, and capabilities of the ATS-6 interferometer system was also included as part of this analysis. Since this system has been examined both analytically and experimentally by a number of investigators, and was studied in detail at the beginning of the present investigation, it was believed that such a review would be a valuable supplement to the analytical data. The basic configuration of the ATS-6 system could be adapted for use in navigation/surveillance applications, however, the system hardware does not lend itself easily to adaptation for such use.

TABLE 2-1. APPLICATIONS, ACCURACIES, AND COSTS OF "STRAWMAN" INTERFEROMETER SYSTEMS

System and Application	Position Accuracy	User Equipment Cost, $
System 1: Surveillance/ Data Collection	1-2 km	<1K
System 2: Low Quality Navigation/Surveillance/ Data Transfer	125-500 m	5-10K
System 3: High-Quality Navigation/ Surveillance/Data Transfer	25-75 m	25-50K
System 4: Aerial Navigation/Traffic Control/Data Transfer	250 m	15-20K
System 5: All-Purpose (Navigation/ Surveillance/Data Transfer)	25 m-2 km	<1K-50K

2.1.3 Survey of Competitive Navigation Systems and Comparison With the Interferometry System

A survey of navigation systems, both existing and planned, which are considered to be most competitive with the interferometry system, was conducted. These included: LORAN-C, Omega, TRANSIT, NAVSTAR/GPS, MARSAT, AEROSAT, and some of the NASA-sponsored experiments such as OPLE, GRAN, IRLS, and PLACE. The principles involved in these systems, their characteristics and configurations were reviewed, and the systems were subsequently compared with each other and with the five strawman interferometer systems on the basis of principal characteristics and performance. The most important of the capabilities/characteristics considered are:

(1) Coverage

(2) Accuracy of positioning

(3) Ability to provide continuous positioning update

(4) Capability to meet a variety of user requirements (surveillance, navigation, data transfer)

(5) Number of users that can be accommodated at any given time

(6) Cost of the user subsystem.

The results of the comparison showed:

(1) Coverage: Omega, TRANSIT, and NAVSTAR/GPS provide global coverage. All of the other systems* (including the interferometer systems), except LORAN-C, can, by various additions/ modifications provide global coverage (excluding the polar regions).

(2) Position Accuracy: The positioning accuracy of the interferometer-systems depends principally on the baseline length and the random component of the phase-difference measurement. With a 50-m baseline, the accuracy is comparable to that obtained with the NAVSTAR/GPS which is the best of all of the competitive navigation systems.

(3) Update Interval: All of the systems, except TRANSIT, have almost continuous positioning capability so long as the user is within range of the system.

(4) User Applications: All of the interferometer systems and OPLE and PLACE have surveillance capability. Interferometer Systems 2 through 5 can provide 2-D navigation capability, as can LORAN-C Omega, PLACE, MARSAT, AEROSAT, and TRANSIT; NAVSTAR/GPS is expected to have 3-D capability. Interferometer Systems 2 through 5 have data-transfer capability, as do PLACE, MARSAT, and AEROSAT; the other systems do not.

(5) Number of Users: LORAN-C, Omega, TRANSIT, and NAVSTAR/GPS are insaturable with regard to the number of users since they operate in the passive mode. Interferometer System 1 can accommodate nearly an unlimited number of users. The other systems are limited by design capabilities, however, the number of users can be increased by providing time multiplexing to permit users requiring the same update intervals to share the same channel. For example, Interferometer Systems 2, 3, and 5 can have more than 100,000 users if their required update interval is between 10 and 30 minutes, but

* GRAN and IRLS were not considered in this comparison since they are no longer active. OPLE, although no longer active, was considered however, because it formed the basis for the on-going PLACE experiment.

only about 500 to 1000 users can be accommodated if they require continuous updating.

(6) Cost of User Subsystem: Based on preliminary cost estimates, it appears that Interferometer System 1 and OPLE would be least expensive (less than \$1000); TRANSIT and Interferometer System 3 would be most expensive (more than \$25,000), although System 3 would be still much less expensive than TRANSIT to provide similar capabilities. Interferometer System 2 would cost about \$5,000 to \$10,000, Interferometer System 4 would cost about \$15,000 to \$20,000 and Interferometer System 5 (combination of Systems 1, 2, and 3), could range from \$1000 to \$50,000 depending on user requirements. Costs for MARSAT and AEROSAT are unavailable, but possibly would be about \$20,000. Costs for PLACE are unavailable. LORAN-C and Omega would cost from \$3,000 to \$5,000 (Marine) to \$25,000 - \$35,000 (airborne); from \$13,000 to \$30,000 (design goal cost).

In general, then, it may be said that the performance of NAVSTAR/GPS is the best of the systems having only navigation capability. It does not have the capability for other applications, however. The interferometer systems, overall, rank higher in performance than other similar all-purpose systems, and the performance of Systems 2 and 5 is rated outstanding.

2.1.4 Preliminary Assessment of User Interests

In order to identify some of the existing and possible requirements and applications of potential users of interferometry systems, a limited effort was undertaken which involved both a survey of the literature on past programs and studies, and a series of interviews with a small number of selected individuals in Government and industry.

Seven types of user groups were represented in the survey: shipping, fisheries, specialized operations, search/rescue and salvage, data collection, law enforcement, and civil air. The capabilities of the five strawman systems were correlated with these various user applications. It is emphasized that the results of the literature search and survey must be regarded as preliminary. The results of the survey, by user area, are summarized below.

2.1.4.1 Shipping. Most of the shipping industry requirements can be met by the interferometer system. The biggest application would be for ship navigation and data transfer on the high seas for which the low-accuracy navigation capability of System 2 (125 to 500 m)* would be adequate. Their position-location accuracy requirements of 200 m to 2 km at update intervals of 10 to 30 minutes offer no particular limitation on the system. More frequent update intervals and greater accuracy would be required by those users operating near coastal areas, the Gulf of Mexico, in shipping lanes, and approaches to harbors. A combination of Systems 2 and 3 or 5 could satisfy their requirements. Further analysis will be necessary to determine the number of channels required per given operation and the specific update intervals needed. The interferometer surveillance capability (System 1) may be of interest to large companies to monitor their worldwide operations as well as to the Coast Guard for collision avoidance, harbor approach, and traffic control.

Interviews with shipping and tanker company personnel indicated that they have requirements for communications, particularly for weather routing and in sending telex messages concerning shipboard problems, diversion of tankers to other ports, relay of engine data, payroll data, etc.

2.1.4.2 Fisheries. As of January, 1973, the U.S. had about 19,350 commercial fishing vessels which harvested about 5 billion pounds of fish per year worth over $800 million. The fishing industry has a need for high accuracy in position location for certain types of operations, to make them economically feasible. Fishermen, however, require inexpensive equipment that is simple to operate, reliable, and relatively small in size. Most of the requirements of the fisheries can be met with Interferometer System 2. Their need, however, for continuous positioning data may impose some limitations on the number of users that can be accommodated. Research vessels and other categories such as bottom trawl and pots, have requirements for the highest positioning accuracy (25 to 200 m) which can be met with System 3 but at a higher cost.

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*Refer to Table 2-1 for a summary of strawman interferometer systems application capabilities.

2.1.4.3 Specialized Operations. Specialized operations, such as hydrographic charting, determination of marine boundaries, geophysical exploration for oil and minerals, pipeline and cable laying, oceanographic surveys, etc., have needs for highly accurate navigation systems which can provide near-continuous position updating information. Interferometer System 3 or 5 appears to be most suitable for these types of operations. Accuracy in position location is of greatest interest to most of these users who invest substantially in navigation equipment ($200,000 to $1 million per ship). Although they represent only a small number of users of navigation systems (less than 1500), they serve various functions and industries with gross sales volumes of several billion dollars annually.

2.1.4.4 Search/Rescue and Salvage. Search and rescue (SAR) operations require position information, communication/surveillance, and coordination among several activities. All SAR functions could be served most effectively by the interferometer systems. If only surveillance capability is required, System 1 could be used for locating the emergency alarm signal of a craft in distress to an accuracy of 1 to 2 km. If, in addition, coordinating and search activities are required, Systesm 2 through 5 could be used. Present SAR operations have many limitations (e.g., false alarms, aerial coverage, line of sight radio frequencies, lack of an effective common datum, surveillance, etc). A satellite-aided SAR system such as the interferometer could alleviate most of the present difficulties, operate effectively, and result in many lives being saved annually.

Retrieval of objects from the ocean floor, whether in rescue operations or for salvage purposes, has basically the same stringent positioning requirements as SAR. Here, the position accuracy requirements are also dictated by the capability and requirements of the submersible vehicle used in conjunction with the surface ships during such operations.

2.1.4.5 Data Collection. Demand for data collection from remote areas and from sensors such as fixed or drifting buoys, platforms, and balloons is increasing. These data often form the basis for establishing "ground truth" for satellite and other systems, and for global models for the atmosphere, environment, ocean circulation, air-sea interface, weather prediction and forecasting, etc. Navigation requirements are for positioning and near-real-time tracking of the various sensors, interrogating them, receiving their data and relaying the data to a ground center for processing and/or dissemination to various users. Interferometer System 1 appears best suited for data collection applications. If data transfer (two-way) is required then Systems 2 through 5 are applicable.

2.1.4.6. Law Enforcement. The requirements of the law enforcement agencies for navigation and communication data vary depending on the nature of the operation. Only two such organizations were contacted during this investigation, the Law Enforcement Division(LED) of the NOAA National Marine Fisheries Service and the Drug Enforcement Administration (DEA). LED has requirements for monitoring the locations of some 1500 U.S. fishing vessels. These requirements consist of: (1) an inexpensive ($1,000 to $1,500) self-contained system that can be placed on ships for location monitoring at 1 to 2-hour intervals, (2) communication/data relay, and (3) receiving an SOS signal in time of emergency. It appears that Interferometer System 1 can accommodate LED requirements.

DEA requirements are for monitoring drug traffic and law enforcement on a worldwide basis. This involves tracking of all types of suspected vehicles and craft (on land, on the ocean, in the air), both cooperative and noncooperative. Because of such diversified requirements all five interferometer systems could be applicable.

2.1.4.7 Civil Air. Civil air requirements vary with the type of aircraft, the function served, and the air space involved. Since the present interferometer system concept has only limited applications to air-traffic control, the civil air requirements were not treated in detail. The small number of channels available (150) for System 4 results from limitations on the aircraft antenna. Design of a mechanically steerable antenna is too complex to be practical. It is possible, however, to design a phased-array antenna that could alleviate these problems and permit an increase in the number of users.

2.2 Conclusions

On the basis of this investigation, some conclusions have been drawn and some technology gaps have been identified. General or overall conclusions are presented immediately below; conclusions resulting from the study of the ATS-6 interferometer system, and directed specifically to possible hardware design improvements for that system, are given in the following subsection (Subsection 2.2.2).

2.2.1 Overall Conclusions

(1) Position determination by the interferometer system can be accomplished using only two reference stations. This is so because of several factors:

(a) The effective change in the baseline length and the nonorthogonality parameters have little effect on the accuracy of the position determination for a baseline less than about 40 to 50 m.

(b) The position accuracy is also independent of any bias that may be inherent in the phase-difference measurements.

(c) Position accuracy is not very sensitive to the satellite ephemeris.

However, for longer baselines, the technique applied in this investigation, is capable of determining the error model parameters simultaneously using more reference stations.

(2) The accuracy of determination of satellite positons by the satellite interferometry technique is too poor to be competitive with other methods that are available at present.

(3) There appears to be a definite interst in and trend among various user communities regarding the acquisition of multicapability systems (navigation, communication/data transfer, surveillance, etc.). The interferometer systems can be competitive in meeting their requirements. Some industrial users who are interested in high position-accuracy capability are expecting that their requirements would be met by the DOD/GPS system. However, it is believed that the DOD has not made a final decision on the allowable extent of civilian use of the GPS system. Further, it has been suggested (Aerospace Daily, March 2, 1976, page 11) that interferometry will, eventually, by the year 2000, replace the GPS system with no loss of capability. Consequently, NASA should continue to study and experiment an interferometer system such as Systems 3 or 5.

(4) Longer baselines are necessary to achieve the position accuracy required by many of the potential interferometry applications and to make the interferometer system competitive with other navigation systems. This means longer booms (of the order of 25 to 100 m) will be required.

(5) The inability to provide a significant air-traffic control capability is a major limitation of a current state-of-the-art interferometer positioning system. In particular, increased accuracy over the 250 m specified for "strawman" System 4, as well as the provision of a voice channel would enhance the utility of an interferometer system. In addition, to provide high-quality navigation or positioning requires the use of a steerable tracking antenna which is currently envisioned as being a fixed-aperture antenna that is mechanically moved so as to track the spacecraft. The availability of an electronically steered phased-array antenna for the aircraft antenna would allow a complete air-traffic control capability to be provided by an interferometer system as well as eliminate the necessity for a large mechanically steered antenna mount for high-accuracy applications.

Some of the difficulties associated with peak power limitations on the spacecraft transmitter could also be alleviated if a multi-steerable-beam phased array were available at the spacecraft.

2.2.2 Possible Hardware Design Improvements and Conclusions Relative to ATS-6 Interferometer

The analysis of the hardware requirements and limitations for an interferometer system resulted in the identification of a number of design improvements that would be required for an interferometer system capable of providing accurate position information relative to the ATS-6 interferometer hardware configuration. The major requirements are as follows:

(1) A considerably longer baseline is necessary than that used with the ATS-6. If a data-transfer capability is to be provided, then the predetection signal-to-noise ratio must be maintained at about +13 db or above in order to limit the bit

error rate to below 10^{-6}. In general, this requires using lower frequencies than the 6 GHz used by the ATS-6. Unless the baseline length is increased, poorer position accuracy will result. In addition, the use of longer baselines will allow very accurate position measurements to be made without requiring excessively large ground-antenna assemblies. Analysis of both the effects of baseline nonorthogonality and uncertainties in the baseline lengths and the baseline deformation and motions to be expected as a result of thermal effects and spacecraft movement and vibration indicates that, for a well-designed boom structure, baseline lengths of up to 100 m should be within the current state of the art.

(2) The interferometer receiver used for positioning applications must have much narrower predetection bandwidths than that used by the ATS-6. This could be mechanized by using multiple tracking phase-locked loops or by digitally forming a series of narrow-band comb filters. The factors of importance are the differential phase bias introduced by whatever hardware realization is used and the dynamic range required to accommodate various signal levels.

(3) The square-law detector used in the ATS-6 is not suitable for a positioning system. The detection loss can be minimized by the use of a different demodulation technique. Either a phase-locked loop technique or a remodulation approach with the resultant generation of a phase-locked unmodulated reference carrier combined with a phase-metering technique which avoids phase measurements at those times at which the modulation-phase reversals occur should result in minimum detection loss and an insignificant effect on the phase-measurement accuracy by the data modulation.

The design and development of an interferometer system which differs from the ATS-6 configuration in the above areas should result in a system capable of demonstrating the positioning capabilities of geostationary satellite interferometry.

Consideration has been given as to whether the existing ATS-6 interferometer hardware can be modified so as to be suitable for use in a demonstration experiment. The major difficulty with the ATS-6 hardware is the requirement for a very large effective radiated power (ERP) from the ground transmitter in order to activate the receiver AGC and the digital phase meter. To function with an ERP which is realistic in terms of a navigation system requires either (1) that the range to the spacecraft be reduced substantially, meaning that only an orbital satellite could be used as the interferometer platform, or (2) substantial redesign of the intermediate frequency amplifiers and filter assemblies in the ATS-6 hardware to reduce the predetection bandwidth by a factor of 2 to 3 orders of magnitude. The first alternative is not desirable in that a system demonstration on a geostationary spacecraft is necessary to convince potential users of the viability of interferometry for positioning and data transfer. The second alternative is anticipated to be quite expensive, and (if combined with detector changes and an increase in the baseline lengths) amounts in essence to the design of a new system, although it is anticipated that some ATS-6 components could be used.

2.3 Recommendations

The results of the studies, analyses, and surveys which were conducted in this program revealed the following:

- Geostationary satellite interferometry represents a viable alternative to current and other proposed navigation and positioning techniques.
- The user hardware cost and the attainable position accuracies are competitive with other techniques and additional capabilities not possible with other systems, such as two-way data transfer, can be provided.
- To insure that the potential of interferometry can be realized requires experimental demonstration of its capabilities as soon as possible.

In the light of these results and the conclusions which have been drawn from them, it is strongly recommended that NASA initiates a long-range development program leading first to a flight demonstration and ultimately to a prototype interferometer positioning system. The major elements which should be incorporated into such a program are discussed briefly below:

(1) In order to design an optimal interferometer system, i.e., one that will provide the greatest number of capabilities for the greatest number of users, the user requirements should be examined in more detail. To do this an in-depth survey of the potential user community needs to be conducted to determine user applications and requirements more precisely.

(2) An examination of the two-way data link requirements between a spacecraft interferometer and a central processing site needs to be carried out as a function of the interferometer system configuration and the various user applications and numbers of users.

(3) Additional analysis of long interferometer booms (25 to 100 m) should be undertaken, since longer baselines are essential if the interferometer system is to compete with other navigation systems with regard to accuracy. The present analysis indicated that longer booms cause no significant problems with system performance as a result of thermal effects or vibration. Such an effort should include analysis, construction, and thermal testing in a vacuum chamber of scale models, as well as ultimate space-flight testing. The latter could be carried out in conjunction with a suitable interferometer receiver system.

(4) The detailed design of a specific system concept should be undertaken which would be directed toward a particular user group. This design, as implemented, should be capable of demonstrating all of the elements of geostationary satellite interferometry and provide the basis for a future operational system.

(5) Efforts should be initiated on the development of a low- or moderate-cost electronically steered phased-array antenna for use on aircraft, ships, and land vehicles.

Additional areas of research which are suggested for consideration include:

(1) Determination of the precise extent to which multipath effects will contribute to the positioning error for an aircraft user by means of experimental studies of the multipath signal levels and bandspreading as a function of the aircraft altitude, velocity, satellite elevation angle, and underlying terrain.

(2) Experimental determination of the unmodeled contribution to tropospheric refraction errors for elevation angles in the 15^{o} to 30^{o} range is needed. In addition, angle-of-arrival fluctuations due to atmospheric refractive index turbulent irregularities should be measured over the same range of elevation angles. Insofar as possible,these data should be gathered under various climatic conditions and at different seasons of the year.

(3) Examination of the inverse interferometer concept in more detail is needed, with particular attention directed to the development of a realistic error model for this concept as well as possible hardware realizations and user potential.

3.0 SYSTEM ANALYSIS: SOFTWARE

3.1 Concept and Approach

The interferometry system considered in this analysis consists of a pair of baselines at right angles to each other with receiver antennas at each of their ends. This system of antennas is mounted on board a geostationary satellite. The phase difference between the signals received by the antennas at the ends of a baseline from a ground-based microwave transmitter is a measure of the space angle(p,q in Figure 3-1) between the baseline and the direction of the transmitter. Two such angles defined by a pair of baselines at right angles and a transmitter will define the direction of the transmitter with respect to a local rectangular Cartesian coordinate system defined by the pair of baselines. The directions of the baselines with respect to an Earth-fixed system depend on the attitude of the spacecraft which is rarely known. However, the directions to two different transmitters define the space angle between them which is independent of the attitude of the spacecraft. This space angle (A,B) can easily be related to the coordinates of the spacecraft and of the transmitting stations with respect to an earth-fixed system. This relationship forms the mathematical model to be used in this analysis.

Systematic errors that may be caused by unrealistic assumptions are also modeled in this relationship. For example, any deviation from the orthogonality of the baselines or any bias in the phase-difference measurement is properly accounted for in the mathematical model.

The system analysis discussed in this section is directed to determining the conditions under which the unknown station coordinates can be obtained with optimum accuracy. The parameters considered to affect such accuracy are

(1) Baseline lengths
(2) Wavelengths of the transmitted signals
(3) Precision of the phase-difference measurement
(4) Uncertainties in the reference station coordinates
(5) a priori estimate of the satellite position and its accuracy
(6) Geometry of the reference stations

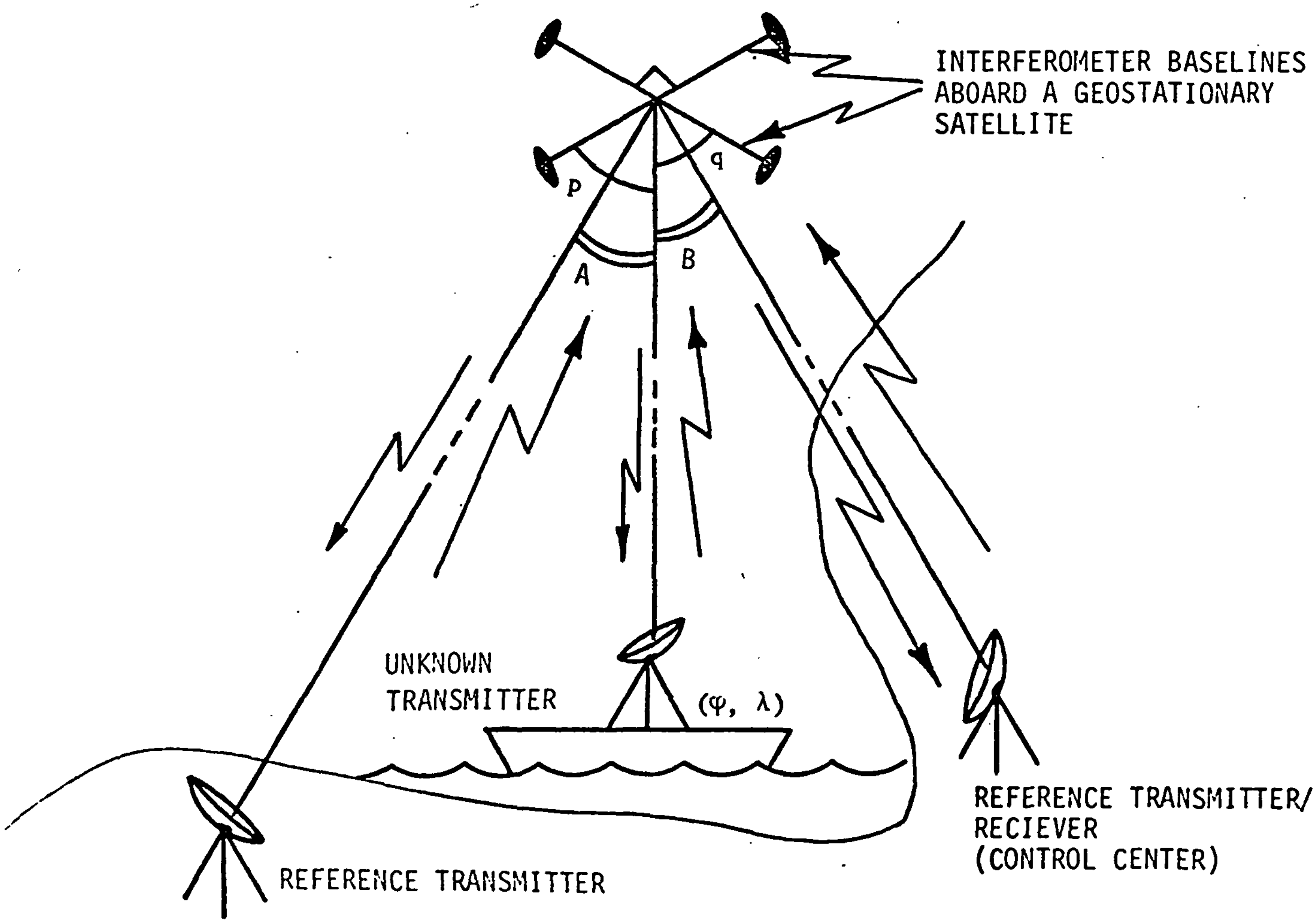


FIGURE 3-1. APPLICATIONS OF INTERFEROMETRY FOR POSITION DETERMINATION

(7) Position of the unknown station with respect to the satellite nadir point

(8) a priori estimates of the unknown station coordinates

(9) Bias in the phase-difference measurement

(10) Nonorthogonality in the baselines

The approach to the analysis is to linearize the mathematical model using Taylor's Series expansion to form a set of condition equations which could be solved using the generalized Least-Squares technique. In this procedure the accuracy estimates of the various "observable" parameters can be propagated into the accuracy estimates of the unknown parameters (unknown station coordinates and the error model parameters) through weighting functions. By "observable" it is meant that these parameters are either directly observed or that there is some a priori knowledge of their values and their accuracy estimates.

The detailed derivation of the mathematical model and all other mathematical tools required for the implementation of the procedure described above are presented in the next section.

3.2 Mathematical Model

The phase difference, $\gamma_{\ell m}$, associated with the baseline, ℓ, and ground station, m, is given by

$$\gamma_{\ell m} = \frac{2\pi L_\ell}{\lambda_m} \cos \theta_{\ell m} + B_\ell \ , \tag{3-1}$$

where B_ℓ is a bias in the phase-difference measurement which is assumed to be constant for a particular baseline, ℓ, whose length is L_ℓ; λ_m is the wavelength of the microwave signal; and $\theta_{\ell m}$ is the angle between the direction of the baseline and of the ground station.

Now, consider a set of two orthogonal baselines which define a local rectangular Cartesian coordinate system aboard a geostationary satellite with baseline 1 along the x-axis and baseline 2 along the y-axis. However, owing to practical limitations of maintaining the orthogonality between the baselines, a small angular error, ϵ, between baseline 2 and the y-axis in the x-y plane is considered as shown in Figure 3-2. The direction, $\bar{b}$, of baseline 2 in the local coordinate system is given in vector notation by

$$\bar{b} = \sin \epsilon \, \bar{x} + \cos \epsilon \, \bar{y} \,, \tag{3-2}$$

where $\bar{x}$, $\bar{y}$ (and $\bar{z}$) are unit vectors along the respective coordinate axes.

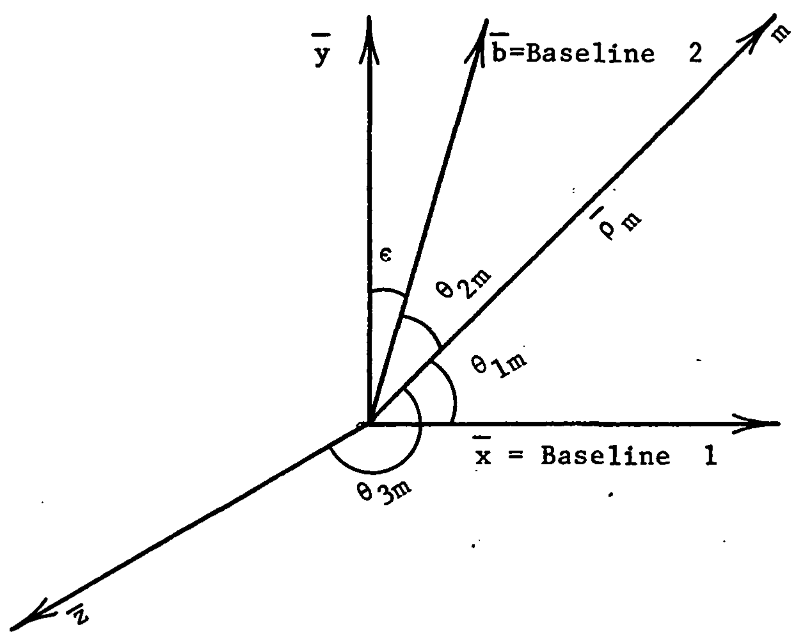


FIGURE 3.2. ALIGNMENT OF THE BASELINES WITH RESPECT TO THE LOCAL COORDINATE SYSTEM

Let the direction cosines of the direction, ρ_m, of the ground station, m, be C_{1m}, C_{2m}, and C_{3m}. Then, in vector notation,

$$\bar{\rho}_m = C_{1m}\bar{x} + C_{2m}\bar{y} + C_{3m}\bar{z} \,. \tag{3-3}$$

These direction cosines are evaluated as follows:

$$C_{1m} = \cos \theta_{1m} , \tag{3-4}$$

which is given by Equation (3-1). The angle between baseline 2 and ρ_m is θ_{2m}, given by

$$\cos \theta_{2m} = \bar{b} \cdot \bar{\rho}_m = C_{1m} \sin \varepsilon + C_{2m} \cos \varepsilon . \tag{3-5}$$

Since ε is amall, Equation (3-5) becomes

$$\cos \theta_{2m} = C_{1m} \varepsilon + C_{2m} , \tag{3-6}$$

which, when rearranged, gives

$$C_{2m} = \cos \theta_{2m} - \varepsilon C_{1m} . \tag{3-7}$$

Then,

$$C_{3m} = (1 - C_{1m}^2 - C_{2m}^2)^{1/2} . \tag{3-8}$$

Similarly, the direction, $\bar{\rho}_n$, to a second ground-based transmitter, n, can be written as follows:

$$\bar{\rho}_n = C_{1n} \bar{x} + C_{2n} \bar{y} + C_{3n} \bar{z} . \tag{3-9}$$

Then, the angle, φ, between these directions $(\bar{\rho}_m, \bar{\rho}_n)$ is given by

$$\cos \varphi = \bar{\rho}_m \cdot \bar{\rho}_n = C_{1m} C_{1n} + C_{2m} C_{2n} + C_{3m} C_{3n} . \tag{3-10}$$

It is important to note that Equation (3-10) is independent of the attitude of the satellite which, however, has a marginal limitation on the hardware of the system to measure the phase differences.

Now, let us examine how this angle can be related to the positions of the ground stations and the satellite in an earth-fixed system of coordinates. Suppose that the coordinates of the ground stations are X, Y, Z with appropriate subscripts m or n depending on which station is referred to. If the coordinates of the satellite are X_s, Y_s, and Z_s, the direction, $\overline{S}_m$, of the satellite from the station, m, is given by

$$\overline{S}_m = (X_s - X_m)\overline{i} + (Y_s - Y_m)\overline{j} + (Z_s - Z_m)\overline{k} \;, \tag{3-11}$$

where $\overline{i}$, $\overline{j}$, and $\overline{k}$ are unit vectors along the respective axes of the earth-fixed coordinate system. Similarly, the direction, $\overline{S}_n$, from the station, n, to the satellite is given by

$$\overline{S}_n = (X_s - X_n)\overline{i} + (Y_s - Y_n)\overline{j} + (Z_s - Z_n)\overline{k} \;. \tag{3-12}$$

The space angle between these two vectors ($\overline{S}_m$, $\overline{S}_n$) is φ which is given by Equation (3-10). Then,

$$\begin{aligned} \cos\varphi &= \overline{S}_m \cdot \overline{S}_n \\ &= \frac{(X_s - X_m)(X_s - X_n) + (Y_s - Y_m)(Y_s - Y_n) + (Z_s - Z_m)(Z_s - Z_n)}{|\overline{S}_m| \;\; |\overline{S}_n|} \end{aligned} \tag{3-13}$$

where

$$|\overline{S}_m| = \left[(X_s - X_m)^2 + (Y_s - Y_m)^2 + (Z_s - Z_m)^2\right]^{1/2} \;, \tag{3-13a}$$

and

$$|\overline{S}_n| = \left[(X_s - X_n)^2 + (Y_s - Y_n)^2 + (Z_s - Z_n)^2\right]^{1/2} \;. \tag{3-13b}$$

Consequently, from Equations (3-10) and (3-13)

$$C_{1m}\,C_{1n} + C_{2m}\,C_{2n} + C_{3m}\,C_{3n}$$

$$= \frac{(X_s-X_m)(X_s-X_n) + (Y_s-Y_m)(Y_s-Y_n) + (Z_s-Z_m)(Z_s-Z_n)}{|\bar{S}_m|\;|\bar{S}_n|} \,. \tag{3-14}$$

Thus Equation (3-14) establishes the relationship between the observables (phase differences) and the station coordinates, some of which are unknowns.

Since all the interferometric measurements are angular and define only the directions to the unknown stations, at least one distance measurement to each of the unknown stations is necessary for the problem to be deterministic. This distance may be from the satellite, from a reference station, or from a given surface. The most practical and realistic of these alternatives is to constrain the unknown station to a reference ellipsoid or at a given distance from the ellipsoid with appropriate weights. The mathematical model for such a weighted constraint will be discussed next.

3.2.1 Mathematical Model for Constraints

The geocentric radius of a point on the reference ellipsoid can be written as

$$r = \frac{a\sqrt{1-e^2}}{\sqrt{1-e^2\cos^2\bar{\varphi}}} \;, \tag{3-15}$$

where, a and e are, respectively, the semi-major axis and the eccentricity of the reference ellipsoid, and $\bar{\varphi}$ is the geocentric latitude of the point under consideration. If the height of the point above the ellipsoid is H then,

$$r + H \simeq (X^2+Y^2+Z^2)^{1/2} = R \;, \tag{3-16}$$

where, X, Y, and Z are the rectangular Cartesian coordinates of the point in an earth-fixed system. Approximately equal sign ($\simeq$) is used instead of equal sign (=) because the quantities r and H are not measured in the same direction. However, the error introduced as a result, would be negligible compared to that introduced due to the relatively large uncertainty in H.

The latitude in Equation (3-15) is computed from the following equation

$$\cos^2\bar{\varphi} = \frac{(X^2+Y^2)}{R^2} \quad . \tag{3-17}$$

However, X, Y, and Z are unknowns. Consequently, Equations (3-14) through (3-17) have to be solved in an iterative procedure as follows.

Owing to the nonlinear nature of these equations, we would need some a priori estimates for X, Y, and Z. Let the subscripts 0, 1,... denote the values of the quantities involved in the zeroth, first,... iterations

$$R_o = (X_o^2+Y_o^2+Z_o^2)^{1/2} \ , \tag{3-18}$$

$$\cos^2\bar{\varphi}_o = (X_o^2+Y_o^2)/R_o^2 \ , \tag{3-19}$$

$$r_o = a\sqrt{(1-e^2)}\Big/\sqrt{1-e^2\cos^2\bar{\varphi}_o} \tag{3-20}$$

Then, the constraint Equation (3-16) becomes

$$r_o + H = \sqrt{X^2+Y^2+Z^2} \quad . \tag{3-21}$$

Solution of Equations (3-14) and (3-21) gives new estimates X_1, Y_1, Z_1 for X, Y, Z, respectively. These new estimates will result in new values R_1, $\bar{\varphi}_1$, and r_1, from Equations (3-18) through (3-21). This procedure is continued till there is no change in the values of X, Y, Z in two consecutive iterations.

3.2.2 Solution for the Unknown Station Positions

The coordinates of the unknown station can be obtained by solving a combined set of equations of the type of (3-14) and (3-16) which are very complex and nonlinear. Let us, now, consider the number of unknown and known quantities. By the word "known" is meant that these quantities are obtained from direct observation or are based on a priori information. For example, the phase differences are measured. The wavelengths of the transmitted signals, and coordinates of reference stations, although associated with uncertainties, have a priori information available on them. On the other hand, the nonorthogonality parameter, ϵ, phase-difference biases, baseline lengths, satellite coordinates, and coordinates of the unknown station can be considered unknowns. If necessary, the satellite (geostationary) coordinates, in an earth-fixed system, are known to a reasonable accuracy from tracking data. The solution from a combination of observed data and a priori information will be optimal in the sense that it gives the best results with the available data.

Equation (3-14) can be rearranged as follows:

$$C_{1m}\,C_{1n} + C_{2m}\,C_{2n} + C_{3m}\,C_{3n} - \Big[(X_s-X_m)(X_s-X_n) + (Y_s-Y_m)(Y_s-Y_n) \qquad (3\text{-}22)$$

$$+ (Z_s-Z_m)(Z_s-Z_n)\Big] \Big/ |\bar{S}_m||\bar{S}_n| = 0 \quad .$$

Writing

$$F_1 = \sum_{i=1}^{3} C_{im}C_{in} \quad , \qquad (3\text{-}23)$$

and

$$F_2 = -\frac{\Big[(X_s-X_m)(X_s-X_n) + (Y_s-Y_m)(Y_s-Y_n) + (Z_s-Z_m)(Z_s-Z_n)\Big]}{|\bar{S}_m| \; |\bar{S}_n|} \quad , \qquad (3\text{-}24)$$

Equation (3-22) can be written in a general form

$$F_1(\gamma_{\ell m},\gamma_{\ell n},B_\ell,L_\ell,\lambda_m,\lambda_n,\varepsilon,\ell = 1,2) \tag{3-25}$$

$$+ F_2(X_s,Y_s,Z_s,X_m,Y_m,Z_m,X_n,Y_n,Z_n) = 0 \ .$$

The quantities within parentheses indicate that F_1 and F_2 are functions of those quantities. Equation (3-16) can be rearranged and written in the general form as

$$F[(r+H),\ X,\ Y,\ Z] \equiv r+H-(X^2+Y^2+Z^2)^{1/2} = 0 \ . \tag{3-26}$$

The general mathematical model given in Equation (3-25) can be modified to include Equations of the type (3-26) and written as

$$F_1[\gamma_{\ell m},\gamma_{\ell n},B_\ell,L_\ell,\lambda_m,\lambda_n,\varepsilon,(r+H),\ell = 1,\ 2] \tag{3-27}$$

$$+ F_2(X_s,Y_s,Z_s,X_m,Y_m,Z_m,X_n,Y_n,Z_n) = 0 \ .$$

For the purpose of combining the observational data with the a priori information, every parameter contained in Equation (3-27) is considered an observable with an associated standard deviation which is a measure of the uncertainty in the a priori information. If there is no a priori information on a parameter, the standard deviation is set to infinity. On the other hand, if a parameter is completely known, the standard deviation is set to zero. In this case, Equation (3-27) would be a condition equation. Linearizing Equation (3-27) and writing the resulting equation in matrix notation, we have

$$B_o V + W = 0 \quad , \tag{3-28}$$

where V is the vector of residuals on all the observables, W is the misclosure vector obtained by evaluating Equation (3-27) with the observed or a priori values for all the parameters, and B_o is the matrix of partials with respect to all the observables. If the variance-covariance matrix of these observables is Σ_o then, the Least-Squares solution of the residuals, V, is given by

$$V = -\Sigma_o B_o^T M^{-1} W \quad , \tag{3-29}$$

where

$$M = B_o \Sigma_o B_o^T \quad , \tag{3-30}$$

with the superscript T indicating the transpose of a matrix.

The quantities which are directly observed or those which are well known will be given high weights. On the other hand, the quantities having poor a priori information will be weighted very low. This uneven weight assignment may, sometimes, cause numerical problems in the inversion of the M matrix as used in Equation (3-29). Consequently, the quantities with low weights are partitioned from those with high weights and the resulting condition equation corresponding to Equation (3-28) will be of the form

$$BV + AV_x + W = 0 \quad , \tag{3-31}$$

where B and A are given by

$$B_o = \begin{bmatrix} B & A \end{bmatrix} \quad , \tag{3-32}$$

with V being the residuals on the quantities with high weight, hereinafter referred to as observables. V_x is the vector of residuals on quantities with low weights, hereinafter referred to as parameters. If Σ_o is also partitioned along the same line as

$$\Sigma_o = \begin{bmatrix} \Sigma & 0 \\ 0 & \Sigma_x \end{bmatrix} , \tag{3-33}$$

and assuming no correlation between the two sets, the Least Squares solutions to the residuals are given by

$$V_x = -\left[A^T M^{-1} A + \Sigma_x^{-1}\right]^{-1} A^T M^{-1} W \quad , \tag{3-34}$$

and

$$V = -\Sigma B^T M^{-1}(AV_x+W) \quad . \tag{3-35}$$

The mathematical model [combination of Equations (3-22) and (3-26)] used in this analysis is very nonlinear and as such the solutions given by Equations (3-34) and (3-35) are only first-order approximations to the correct ones. This situation calls for an iterative solution where the point of linearization for one iteration would be about the adjusted values after the previous iteration. This will make the residuals V and V_x no longer the difference between the observed or the a priori values and the adjusted values with variance-covariance matrices Σ and Σ_x. Consequently, the W matrix has to be modified as follows (Pope, 1972):

$$W_i = F_{1i} + F_{2i} + AV_{x_{i-1}} + BV_{i-1} \quad , \tag{3-36}$$

where the subscript i and i-1 refer to the values at the ith and (i-1)th iteration. The a posteriori variance-covariance matrix, Q_x, of the parameters is given by

$$Q_x = \sigma_o^2(A^T M^{-1} A + \Sigma_x^{-1})^{-1} \quad , \tag{3-37}$$

where σ_o^2 is the variance of unit weight which is computed from

$$\sigma_o^2 = \frac{V^T \Sigma^{-1} V + V_x^T \Sigma_x^{-1} V_x}{DF} \quad , \tag{3-38}$$

with DF being the number of degrees of freedom.

3.2.3 Partial Derivatives

In the partition discussed earlier, the observables considered are

(1) Phase differences
(2) Wavelengths of the transmitted signals
(3) Coordinates of the reference stations,

and the parameters are

(1) Nonorthogonality parameter
(2) Biases (two, one associated with each baseline)

(3) Baseline lengths

(4) Satellite coordinates

(5) Unknown station coordinates.

According to this partition, the partials of the functions F_1 and F_2 with respect to the observables evaluated at the point of linearization form the elements of matrix B. The partials of these functions with respect to the parameters, similarly evaluated, form the elements of A.

3.2.3.1 Partials with Respect to Phase Differences (γ). Using Equations (3-1) and (3-4),

$$C_{1m} = \frac{(\gamma_{1m} - B_1)\lambda_m}{2\pi L_1} \quad , \tag{3-39}$$

and from Equations (3-1) and (3-7)

$$C_{2m} = \frac{(\gamma_{2m} - B_2)\lambda_m}{2\pi L_2} - \frac{\epsilon(\gamma_{1m} - B_1)\lambda_m}{2\pi L_1} \quad . \tag{3-40}$$

Differentiating Equation (3-8) with respect to C_{1m} and C_{2m},

$$\delta C_{3m} = -\frac{1}{C_{3m}}(C_{1m}\,\delta C_{1m} + C_{2m}\,\delta C_{2m}) \quad . \tag{3-41}$$

Now, differentiating Equation (3-23) with respect to C_{1m} and C_{2m} we get

$$\frac{\delta F_1}{\delta C_{1m}} = \frac{\delta F_1}{\delta C_{1m}} + \frac{\delta F_1}{\delta C_{3m}} \frac{\delta C_{3m}}{\delta C_{1m}} \tag{3-42}$$

$$= C_{1n} - C_{3n}\frac{C_{1m}}{C_{3m}}$$

and

$$\frac{\delta F_1}{\delta C_{2m}} = C_{2n} - C_{3n}\frac{C_{2m}}{C_{3m}} \tag{3-43}$$

Due to the symmetry of F_1 in m and n, $\frac{\partial F_1}{\partial C_{1n}}$ and $\frac{\partial F_1}{\partial C_{2n}}$ can be written as follows

$$\frac{\partial F_1}{\partial C_{1n}} = C_{1m} - C_{3m}\frac{C_{1n}}{C_{3n}} \quad , \tag{3-44}$$

$$\frac{\partial F_1}{\partial C_{2n}} = C_{2m} - C_{3m}\frac{C_{2n}}{C_{3n}} \quad . \tag{3-45}$$

Equations (3-42) through (3-45) can be written notationally in a general form

$$\frac{\partial F_1}{\partial C_{\ell m(n)}} = \rho_{\ell m(n)} = C_{\ell n(m)} - \frac{C_{3n(m)}\, C_{\ell m(n)}}{C_{3m(n)}}, \ \ell = 1,2 \quad . \tag{3-46}$$

Differentiating Equations (3-39) and (3-40),

$$\partial C_{1m(n)} = \frac{\lambda_{m(n)}}{2\pi L_1}\left[\partial\gamma_{\ell m(n)} - \partial B_1\right] + \frac{C_{1m(n)}}{\lambda_{m(n)}}\,\partial\lambda_{m(n)} - \frac{C_{1m(n)}}{L_1}\,\partial L_1 \tag{3-47}$$

$$\partial C_{2m(n)} = \frac{\lambda_{m(n)}}{2\pi L_2}\left[\partial\gamma_{2m(n)} - \partial B_2\right] + \frac{C_{2m(n)}}{\lambda_{m(n)}}\,\partial\lambda_{m(n)} - \frac{(\gamma_{2m(n)} - B_2)\lambda_{m(n)}}{2\pi L_2^2}\,\partial L_2$$

$$- \epsilon\left[\frac{\lambda_{m(n)}}{2\pi L_1}(\partial\gamma_{1m(n)} - \partial B_1) + \frac{C_{1m(n)}}{\lambda_{m(n)}}\,\partial\lambda_{m(n)} - \frac{C_{1m(n)}}{L_1}\,\partial L_1\right] \tag{3-48}$$

$$+ C_{1m(n)}\partial\epsilon \quad .$$

Consequently, from Equations (3-46) through (3-48)

$$\frac{\partial F_1}{\partial\gamma_1} = \frac{\partial F_1}{\partial C_{1M}}\frac{\partial C_{1m}}{\partial\gamma_{1m}} + \frac{\partial F_1}{\partial C_{2m}}\frac{\partial C_{2m}}{\partial\gamma_{1m}}$$

$$= \frac{\lambda_m}{2\pi L_1}(\rho_{1m} - \epsilon\rho_{2m}) \quad . \tag{3-49}$$

$$\frac{\partial F_1}{\partial \gamma_{2m}} = \rho_{2m} \frac{\lambda_m}{2\pi L_2} \quad . \tag{3-50}$$

Similarly,

$$\frac{\partial F_1}{\partial \gamma_{1n}} = \frac{\lambda_n}{2\pi L_1} (\rho_{1n} - \epsilon\rho_{2n}) \tag{3-51}$$

and

$$\frac{\partial F_1}{\partial \gamma_{2n}} = \frac{\lambda_n}{2\pi L_2} \rho_{2n} \quad . \tag{3-52}$$

<u>3.2.3.2 Partials with Respect to Wavelengths (λ)</u>. Differentiating Equation (3-23) with respect to λ_m,

$$\frac{\partial F_1}{\partial \lambda_m} = \frac{\partial F_1}{\partial C_{1m}} \frac{\partial C_{1m}}{\partial \lambda_m} + \frac{\partial F_1}{\partial C_{2m}} \frac{\partial C_{2m}}{\partial \lambda_m}$$

$$= \rho_{1m} \frac{C_{1m}}{\lambda_m} + \rho_{2m} \frac{C_{2m} - \epsilon C_{1m}}{\lambda_m} \tag{3-53}$$

$$= \frac{1}{\lambda_m} \left[C_{2m}\rho_{2m} + C_{1m}(\rho_{1m} - \epsilon\rho_{2m}) \right] \quad .$$

Similarly,

$$\frac{\partial F_1}{\partial \lambda_n} = \frac{1}{\lambda_n} \left[C_{2n\ 2b} + C_{1n}(\rho_{1n} - \epsilon\rho_{2n}) \right] \quad . \tag{3-54}$$

<u>3.2.3.3 Partials with Respect to Non-position Parameters</u>. Differentiating Equation (3-23) with respect to the nonorthogonality parameter, ϵ,

$$\frac{\partial F_1}{\partial e} = \frac{\partial F_1}{\partial C_{2m}} \frac{\partial C_{2m}}{\partial e} + \frac{\partial F_1}{\partial C_{2n}} \frac{\partial C_{2n}}{\partial e} \quad . \tag{3-55}$$

Using Equations (3-46) through (3-48) in (3-55) we get

$$\frac{\partial F_1}{\partial \epsilon} = - \rho_{2m} C_{1m} - \rho_{2n} C_{1n} \quad . \tag{3-56}$$

The partials with respect to the bias terms are derived as follows:

$$\frac{\partial F_1}{\partial B_1} = \frac{\partial F_1}{\partial C_{1m}} \frac{\partial C_{1m}}{\partial B_1} + \frac{\partial F_1}{\partial C_{2m}} \frac{\partial C_{2m}}{\partial B_1} + \frac{\partial F_1}{\partial C_{1n}} \frac{\partial C_{1n}}{\partial B_1} + \frac{\partial F_1}{\partial C_{2n}} \frac{\partial C_{2n}}{\partial B_1}$$

$$= - \frac{\lambda_m}{2\pi L_1} (\rho_{1m} - \epsilon \rho_{2m}) - \frac{\lambda_n}{2\pi L_1} (\rho_{1n} - \epsilon \rho_{2n}) \tag{3-57}$$

$$= - \frac{\partial F_1}{\partial \gamma_{1m}} - \frac{\partial F_1}{\partial \gamma_{1n}} \quad .$$

Similarly,

$$\frac{\partial F_1}{\partial B_2} = - \frac{\partial F_1}{\partial \gamma_{2m}} - \frac{\partial F_1}{\partial \gamma_{2n}} \quad . \tag{3-58}$$

The partials with respect to the baseline lengths are

$$\frac{\partial F_1}{\partial L_1} = - \frac{C_{1m}}{L_1} (\rho_{1m} - \epsilon \rho_{2m}) - \frac{C_{1n}}{L_1} (\rho_{1n} - \epsilon \rho_{2n})$$

which, when using Equations (3-49) and (3-51), reduces to

$$\frac{\partial F_1}{\partial L_1} = - \frac{(\gamma_{1m} - B_1)}{L_1} \frac{\partial F_1}{\partial \gamma_{1m}} - \frac{(\gamma_{1n} - B_1)}{L_1} \frac{\partial F_1}{\partial \gamma_{1n}} \tag{3-59}$$

and

$$\frac{\partial F_1}{\partial L_2} = - \frac{(C_{2m} + \epsilon C_{1m})}{L_2} \rho_{2m} - \frac{(C_{2n} + \epsilon_{1n})}{L_2} \rho_{2n} \quad . \tag{3-60}$$

3.2.3.4 Partials with Respect to Position Parameters and Reference Station Coordinates. The partials with respect to the reference ground station which are assumed to be part of the observables, are similar to those with respect to the unknown station coordinates. Consequently, the derivation of the partials for these two sets of quantities is presented in a common form.

Rewriting Equation (3-24) in a general form, we have

$$F_2 = Q/S_n S_m \quad , \tag{3-61}$$

where

$$Q = -\left\{(X_s-X_m)(X_s-X_n) + (Y_s-Y_m)(Y_s-Y_n) + (Z_s-Z_m)(Z_s-Z_n)\right\}$$

$$S_n = |\bar{S}_n| \tag{3-62}$$

$$S_m = |\bar{S}_m| \; .$$

Differentiating Equation (3-61), we have

$$\partial F_2 = \frac{\partial F_2}{\partial Q}\, dQ + \frac{\partial F_2}{\partial S_n}\, dS_n + \frac{\partial F_2}{\partial S_m}\, dS_m \; , \tag{3-63}$$

where

$$dQ = \frac{\partial Q}{\partial X_s}\, dX_s + \frac{\partial Q}{\partial Y_s}\, dY_s + \frac{\partial Q}{\partial Z_s}\, dZ_s + \sum_{\substack{i=m\\ i=n}} \left(\frac{\partial Q}{\partial X_i}\, dX_i + \frac{\partial Q}{\partial Y_i}\, dY_i + \frac{\partial Q}{\partial Z_i}\, dZ_i\right) \tag{3-64}$$

with

$$\frac{\partial Q}{\partial X_s} = X_m + X_n - 2X_s$$

$$\frac{\partial Q}{\partial Y_s} = Y_m + Y_n - 2Y_s$$

$$\frac{\partial Q}{\partial Z_s} = Z_m + Z_n - 2Z_s$$

$$\frac{\partial Q}{\partial X_{m(n)}} = X_s - X_{n(m)}$$

$$\frac{\partial Q}{\partial Y_{m(n)}} = Y_s - Y_{n(m)} \qquad (3\text{-}65)$$

$$\frac{\partial Q}{\partial Z_{m(n)}} = Z_s - Z_{n(m)}$$

and

$$dS_{m(n)} = \frac{\partial S_{m(n)}}{\partial X_s} dX_s + \frac{\partial S_{m(n)}}{\partial Y_s} dY_s + \frac{\partial S_{m(n)}}{\partial Z_s} \partial Z_s + \frac{\partial S_{m(n)}}{\partial X_{m(n)}} dX_{m(n)} + \frac{\partial S_{m(n)}}{\partial Y_{m(n)}} dY_{m(n)} \qquad (3\text{-}66)$$

$$+ \frac{\partial S_{m(n)}}{\partial Z_{m(n)}} dZ_{m(n)} ,$$

with

$$\frac{\partial S_{m(n)}}{\partial X_s} = \frac{X_s - X_{m(n)}}{S_{m(n)}}$$

$$\frac{\partial S_{m(n)}}{\partial Y_s} = \frac{Y_s - Y_{m(n)}}{S_{m(n)}} \qquad (3\text{-}67)$$

$$\frac{\partial S_{m(n)}}{\partial Z_s} = \frac{Z_s - Z_{m(n)}}{S_{m(n)}}$$

$$\frac{\partial S_{m(n)}}{\partial X_{m(n)}} = - \frac{X_s - X_{m(n)}}{S_{m(n)}}$$

$$\frac{\partial S_{m(n)}}{\partial Y_{m(n)}} = - \frac{Y_s - Y_{m(n)}}{S_{m(n)}} \tag{3-68}$$

$$\frac{\partial S_{m(n)}}{\partial Z_{m(n)}} = - \frac{Z_s - Z_{m(n)}}{S_{m(n)}} \quad .$$

With Equations (3-63) through (3-68) the partials with respect to the satellite coordinates are as follows:

$$\frac{\partial F_2}{\partial X_s} = \frac{X_m + X_n - 2X_s}{S_n S_m} - \frac{(X_s - X_m)Q}{S_n S_m^3} - \frac{(X_s - X_n)Q}{S_m S_n^3} \tag{3-69}$$

$$\frac{\partial F_2}{\partial Y_s} = \frac{Y_m + Y_n - 2Y_s}{S_n S_m} - \frac{(Y_s - Y_m)Q}{S_n S_m^3} - \frac{(Y_s - Y_n)Q}{S_m S_n^3} \tag{3-70}$$

$$\frac{\partial F_2}{\partial Z_s} = \frac{Z_m + Z_n - 2Z_s}{S_n S_m} - \frac{(Z_s - Z_m)Q}{S_n S_m^3} - \frac{(Z_s - Z_n)Q}{S_m S_n^3} \tag{3-71}$$

$$\frac{\partial F_2}{\partial X_{m(n)}} = \frac{X_s - X_{n(m)}}{S_n S_m} + \frac{Q(X_s - X_{m(n)})}{S^3_{m(n)} S_{n(m)}} \tag{3-72}$$

$$\frac{\partial F_2}{\partial Y_{m(n)}} = \frac{Y_s - Y_{n(m)}}{S_n S_m} + \frac{Q(Y_s - Y_{m(n)})}{S^3_{m(n)} S_{n(m)}} \tag{3-73}$$

$$\frac{\partial F_2}{\partial Z_{m(n)}} = \frac{Z_s - Z_{n(m)}}{S_n S_m} + \frac{Q(Z_s - Z_{m(n)})}{S^3_{m(n)} S_{n(m)}} \quad . \tag{3-74}$$

This completes the presentation of the partials which are required to evaluate the elements of both A and B matrices. The vector, W, is defined by Equation (3-36). The variance-covariance matrices, Σ and Σ_x, will be defined from a priori information on the observables and on parameters. Thus, we have all the mathematical tools necessary to perform the analysis of the interferometry system required for position determination.

Before concluding this section, some comments are deemed nacessary about the minimum number of reference stations required to determine the position of an unknown station. We have seen, from the discussion presented earlier in this section, that an equation of the type (3-23) results from combining the data corresponding to two stations. This will mean that, for a total of N-stations, the number of equations would be ${}^{N}C_{2}$ (= N(N-1)/2) which is the number of combinations in N taking 2 at a time. Isley (1972) suggests that these equations, together with those resulting from the constraints, be solved for the parameters. However, these equations are not independent, which is a prerequisite for solving equations of this type. The number of independent equations is (2N-3). The number of unknowns, assuming one unknown station, is 10 [nonorthogonality parameter (1), biases (2), baseline lengths (2), satellite coordinates (3), unknown station coordinates (2) as the third coordinate is constrained]. Consequently, the minimum number of stations (including one unknown station) is given by

$$2N - 3 = 10$$
$$N = 7 \text{ (integer)} .$$

However, it will be shown later that the a priori information available on the satellite coordinates is more accurate than what could be determined from the interferometry. It will also be shown that the biases in the phase-difference measurement have very little effect on the unknown station position. Consequently, the number of unknown parameters reduces to 5 in which case N will take the value 4. This will mean that at least three reference stations are required for the determination of the unknown station under the conditions described. It will be shown that this requirement can be reduced further under certain other circumstances.

3.3 Simulation of Interferometry Data

The concept and the formulae described in the last two sub sections, though theoretically sound, do not provide any physical meaning unless their performance is validated using realistic data. The availability of real data of the type required for this analysis is rather limited. Further, a complete analysis of this system requires many data sets under varied conditions. Consequently, it was decided to use simulated data for verifying this system concept and its performance.

One approach to simulating these data is to solve equations of the type (3-22) backwards for the phase differences in a iterative solution. The major disadvantage in this type of simulation is that the accuracy of the equations and the partials cannot be verified. Such verification is possible only if the data are simulated independent of the equations which are used for the position determination.

The principle used for the simulation in this investigation is based on the assumption of a specific attitude of the satellite which defines the local coordinate system. The directions of the ground stations with respect to this coordinate system are computed and the phase differences are derived using their relationship (Equation 3-1) to these angles. The error model parameters are set to zero. The details of this simulation procedure are presented in the following discussion.

Let X, Y, and Z be the coordinates of the satellite in an earth-fixed system, and assume a local coordinate system at the satellite with axes x, y, and z. Let x-axis be along the radial direction from the earth, let y-axis be along the orbit track, and let z-axis be perpendicular to x and y forming a right-hand system of coordinates. If the satellite is assumed to be on a geostationary orbit in the plane of the equator, the transformation between the XYZ and the xyz systems is given by

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = R_3(\lambda) \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} , \qquad (3\text{-}75)$$

where $R_3(\lambda)$ indicates a rotation through an angle λ about the Z-axis. $R_3(\lambda)$ is explicitly given by

$$R_3(\lambda) = \begin{bmatrix} \cos\lambda & \sin\lambda & 0 \\ \sin\lambda & \cos\lambda & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3-76}$$

then,

$$\begin{aligned} x &= \cos\lambda\ X + \sin\lambda\ Y \\ y &= \sin\lambda\ X + \cos\lambda\ Y \\ z &= Z\ . \end{aligned} \tag{3-77}$$

Now we assume that the two baselines are aligned along y- and z-axes. The direction, $\bar{\rho}_m$, to the ground station, m, with respect to these baselines is given by

$$\bar{\rho}_m = (X-X_m)\ \bar{i} + (Y-Y_m)\ \bar{j} + (Z-Z_m)\ \bar{k}\ , \tag{3-78}$$

where X_m, Y_m, and Z_m are the coordinates of the station m and $\bar{i}$, $\bar{j}$, and $\bar{k}$ are unit vectors along the X-, Y-, and Z-axes, respectively. Then, the angles θ_1 and θ_2 between $\bar{\rho}_m$ and the baselines are given by

$$\begin{aligned} \cos\theta_1 &= \frac{\bar{\rho}.\bar{y}}{|\bar{\rho}|\ |\bar{y}|} \\ &= -\frac{(X-X_m)\ \sin\lambda + (Y-Y_m)\ \cos\lambda}{|\bar{\rho}|}\ , \end{aligned} \tag{3-79}$$

and

$$\cos\theta_2 = \frac{(Z-Z_m)}{|\bar{\rho}|}\ . \tag{3-80}$$

The required phase differences, γ_{1m} and γ_{2m}, can then be computed using Equation (3-1).

$$\gamma_{1m} = \frac{2\pi L_1}{\lambda_m} \cos\theta_1\ , \tag{3-81}$$

$$\gamma_{2m} = \frac{2\pi L_2}{\lambda_m} \cos \theta_2 \quad . \tag{3-82}$$

In order to make the simulation as realistic as possible, some of the parameters selected closely simulate the position of the ATS-6 satellite and the interferometry system aboard it. The position chosen is close to the original position of the ATS-6 with longitude 94°W, latitude 0° and height 42,000 km above the earth. The wavelength of the transmitted signal used is 4.876 cm which corresponds to a frequency of 6 GHz used in the SAPPSAC experiment (Isley, 1975) with the ATS-6 interferometry system. Further reasons for using this frequency range will be discussed in the hardware system analysis presented in the next section.

The criterion used in this selection of the ground stations is the uniformity in distribution around the satellite subpoint. Five stations selected for this investigation are presented in Table 3-1.

TABLE 3-1. GROUND STATIONS SELECTED FOR THE INVESTIGATION

Station No. (NASA)	Name	X (km)	Y (km)	Z (km)
1042	Rosman (USA)	647.4975	-5177.9356	3656.7059
6009	Quito (Ecuador)	1280.8342	-6250.9559	-10.8006
6020	Easter Islands	-1888.6143	-5354.8944	-2895.7490
6038	Soccoro Islands	-2160.9809	-5642.7105	2035.3678
6067	Natal (Brazil)	5186.3971	-3653.9333	-654.2769

Since the analysis required various tests with baselines of different lengths, the observational data were simulated for lengths of 1, 5, and 10 to 50 m at intervals of 10 m.

3.4 Simulation Tests, Results, and Analysis

The accuracy of the unknown station position, as determined by the interferometry system investigated here, depends on the following:

(1) The ratio L/λ as in Equation (3-1)

(2) Uncertainty in the observables
    (a) Phase-difference measurements
    (b) Wavelengths of the transmitted signals
    (c) Coordinates of the reference stations
(3) Nonorthogonality in the baselines
(4) Biases in the phase-difference measurements
(5) Effective change in the baseline lengths
(6) Geometry of the ground-station positions
(7) A priori information on the satellite position
(8) Effect of a priori information on the lengths of the baselines
(9) A priori estimates of the unknown station coordinates

The basic objective of this investigation is to determine the best possible position accuracy obtainable from the interferometry system optimizing the effects of the above factors affecting such accuracy. This objective can be achieved by examining the unknown position accuracy obtained for various combinations of the simulated effects of the above factors.

The accuracies of the unknown parameters are obtained from the variance-covariance matrix given by Equation (3-37). The observations simulated as described in the last sub section do not include any random or systematic errors, i.e., they are perfect observations. The resulting residuals will, therefore, be very small if not zero. Consequently, the variance of unit weight (σ_o^2) computed from Equation (3-38) would also be very small and it would not be realistic to use this small value for σ_o^2 in Equation (3-37) to obtain the variance-covariance matrix, Q_X. However, in a realistic situation, if the weight matrices Σ^{-1} and Σ_x^{-1} are computed properly (absolute rather than relative) with an a priori variance of unit weight unity, in all probability the a posteriori variance of unit weight would also be unity. Therefore, a value of unity is used in Equation (3-37) to evaluate Q_x. Table 3-2 presents the values used for the various parameters in the simulation tests.

The position accuracy, σ_s, in space is given by

$$\sigma_s = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} \quad . \tag{3-83}$$

TABLE 3-2. A PRIORI INFORMATION USED FOR VARIOUS PARAMETERS[(a)]

Parameter	Value	Standard Deviation
ϵ	0.0 radian	1,3,5, ∞ arc sec
B	0.0 radian	0.5,1.0*,∞
L	1*,2,5,10,20 m	10^{-2*} cm,∞
X,Y,Z (unknown stn.)	Table 3-1	∞*
X_s,Y_s,Z_s	φ=0°, λ=266°, h=42,000 km	0.1,1.0*,10.0,100.0 km
γ	Simulated (see Sec. 3.3)	0°1,0°25*,0°5,1°0,2°0
λ	4.876 cm	10^{-5},10^{-6*},10^{-7} cm
X,Y,Z (ref. stns.)	Table 3-1	5,10*,100,1000 m

(a) It is assumed that the height of the unknown station is known to within 50 m. The values marked by an asterisk(*) are considered realistic and are used unless otherwise specified when the value of one parameter is changed to study the effect of such change on the position accuracy of the unknown station.

However, this accuracy is highly correlated to the accuracy of height constraint applied to the coordinates. Therefore, the horizontal component, σ_H, of the position accuracy which is independent of the height constraint, is computed as follows: The North and East components σ_N, σ_E, and the height component, σ_h, are given by (Heiskanen and Moritz, 1967)

$$\begin{bmatrix}\sigma_N\\ \sigma_E\\ \sigma_h\end{bmatrix} = \begin{bmatrix} -\sin\varphi\cos\lambda & -\sin\varphi\sin\lambda & \cos\varphi \\ -\sin\lambda & \cos\lambda & 0 \\ \cos\varphi\cos\lambda & \cos\varphi\sin\lambda & \sin\varphi \end{bmatrix}\begin{bmatrix}\sigma_x\\ \sigma_y\\ \sigma_z\end{bmatrix} \tag{3-84}$$

where φ and λ are the geodetic coordinates of the station.

$$\sigma_H = \sqrt{\sigma_N^2 + \sigma_E^2} \quad . \tag{3-85}$$

As the constraint becomes greater or rather the ratio of height constraint to σ_s becomes smaller, σ_s will approach σ_H. The following discussions present the description, results, and analysis of the simulation tests that were performed to study the effects of the various factors affecting the unknown station position accuracy.

3.4.1 Effects of the Accuracy of the Phase-Difference Measurements

Table 3-3 presents the position accuracy corresponding to the different values of standard deviation of the phase-difference observations.

TABLE 3-3. ACCURACY OF γ VERSUS ACCURACY OF POSITION (L = 1M)

$\sigma\gamma$	σ_H km
$0^\circ.1$	0.80
$0^\circ.25$	1.99
$0^\circ.5$	3.97
$1^\circ.0$	7.94
$2^\circ.0$	15.89

It is seen, from this table, that the position accuracy is directly proportional to the observation accuracy of γ. A graphical presentation of this table of data is given in Figure 3-3.

3.4.2 Effect of Changes in L/λ on Position Accuracy

In this test with λ kept constant, observations are simulated for values of L equal to 1, 2, 5, 10, 15, 20, and 50 m. The corresponding position accuracies for $\sigma_\gamma = 0^\circ.25$ are presented in Table 3-4. The results in Table 3-4 are graphically displayed in Figure 3-4. Predicted values are indicated by broken lines. These results show that the position accuracy is almost inversely proportional to the length, L (or rather L/λ) up to about 20 m and then it shows a tendency to diminish or to become asymptotic. This means the larger the L/λ ratio, the better the position accuracy. However, hardware limitations may prohibit increasing the length of the baseline indefinitely. The predicted results may be used to effect an optimization among position accuracy and baseline length, observational accuracy, and other hardware limitations.

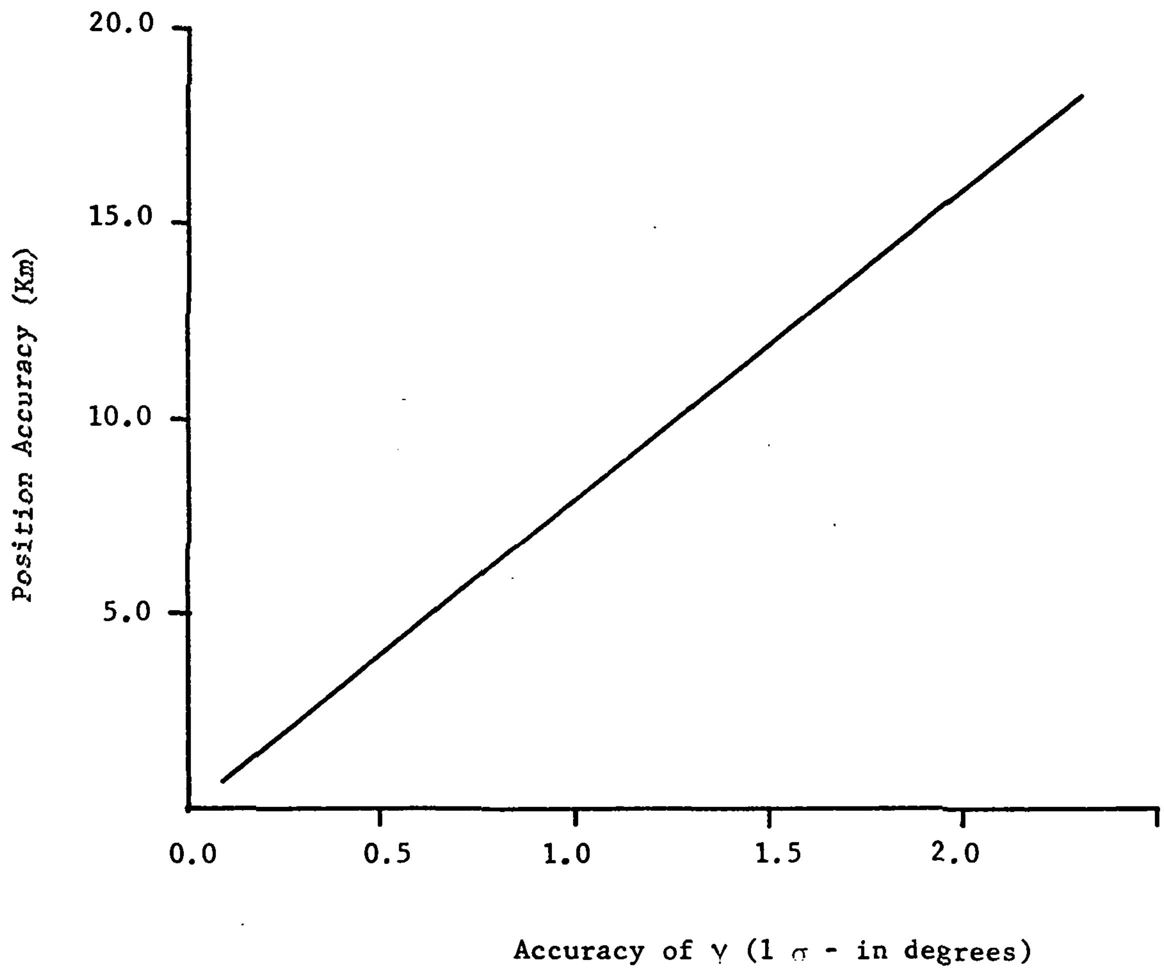


FIGURE 3-3. VARIATION OF POSITION ACCURACY VERSUS ACCURACY OF γ

TABLE 3-4. POSITION ACCURACY FOR CHANGES IN L AND σ_γ

Length, m	$\sigma_H(\sigma_\gamma = 0°.1)$[a]	$\sigma_H(\sigma_\gamma = 0°.25)$	$\sigma_H(\sigma_\gamma = 0°.5)$[a]	$\sigma_H(\sigma_\gamma = 1°.0)$[a]
1	0.80	1.99	3.98	7.96
2	0.40	1.00	2.00	4.00
5	0.16	0.40	0.80	1.60
10	0.08	0.20	0.40	0.80
15	0.06	0.15	0.30	0.60
20	0.04	0.09	0.18	0.36
50	0.02	0.05	0.10	0.20

(a) These values are predicted using the results in Table 3-3 and those in the third column of this table. σ_H is in km.

3.4.3 Effects of Uncertainties in the Wavelengths of the Transmitted Signal

These uncertainties are introduced into the solution through the weight matrix, Σ^{-1}, in the form of variances of the observables. Three solutions obtained with standard deviation, σ_λ, of uncertainties of 10^{-5}, 10^{-6}, and 10^{-7} cm are presented in Table 3-5. The largest error (10^{-5} cm) is roughly equivalent to about 12 kHz, and it is believed that the frequency of the transmitted signals can be controlled to within this limit.

TABLE 3-5. EFFECT OF UNCERTAINTIES IN WAVELENGTHS

σ_λ (cm)	σ_H (km)
10^{-5}	1.9880
10^{-6}	1.9880
10^{-7}	1.9880

These results indicate that changes in λ of the magnitude used do not have any effect on the accuracy of the unknown station position.

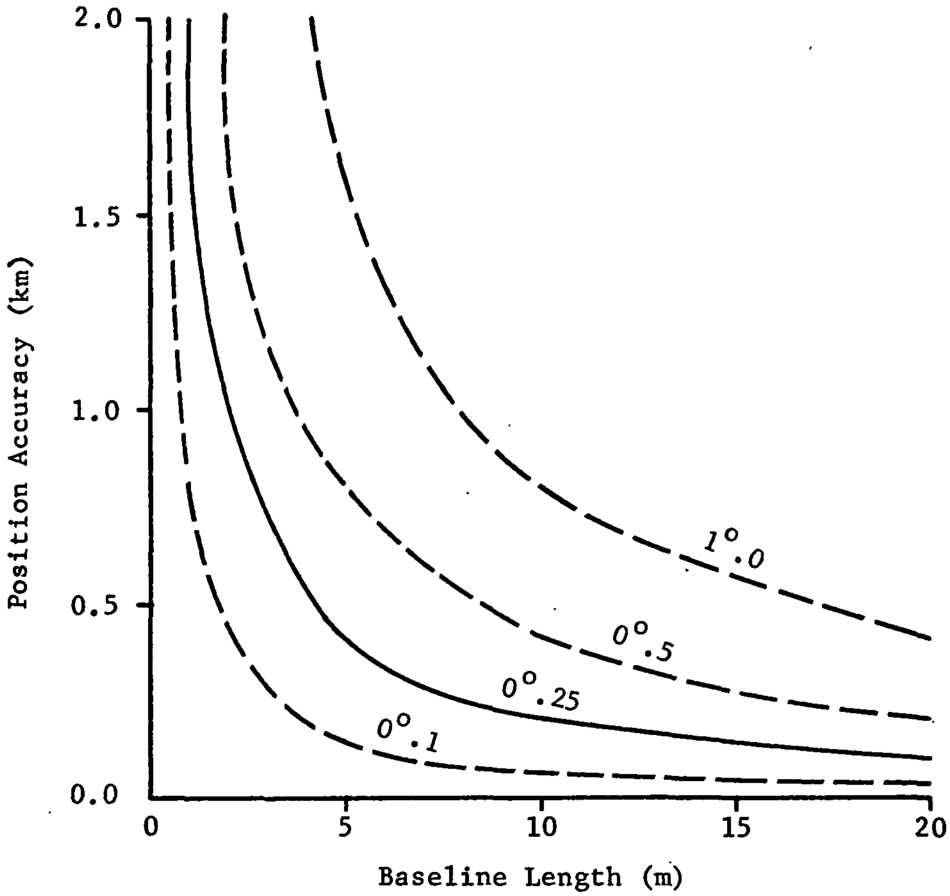


FIGURE 3-4. POSITION ACCURACY AGAINST BASELINE LENGTH AND OBSERVATIONAL ACCURACY

3.4.4 Effects of Uncertainties in the Coordinates of the Reference Stations

These tests are made identical to those in Section 3.4.3 with standard deviations of 10, 100, and 1000 m for the reference station positions. The results are shown in Table 3-6.

TABLE 3-6. EFFECT OF UNCERTAINTIES IN REFERENCE STATION COORDINATES

$\sigma_x, \sigma_y, \sigma_z$ (m)	σ_H (km)	Increase (%)
10	1.988	0.00
100	1.989	0.05
1000	2.112	5.00

It can be seen that errors of the order of 100 m in the reference station coordinates have negligible effect on the position accuracy, while 1000-m errors introduce about 5 percent change. However, most of the stations which can be used as reference stations for the interferometry system are known to about 10 m. Therefore, these errors are not expected to have any effect on the determination of the unknown station coordinates.

3.4.5 Determination of the Error Model Parameters

These parameters include one nonorthogonality parameter, two biases in the phase-difference measurements (one associated with each of the baselines), and two parameters representing the effective lengths of the baselines. How well these parameters can be simultaneously evaluated in this system can be determined by setting the weights corresponding to these parameters in Σ_x^{-1} to zero.

First the solution was tried with the weights for the bias terms set to zero. It was found that the normal equation matrix was unstable indicating that the solution was more or less independent of these bias terms. To obtain more insight into this problem, the element in the design matrix A corresponding to these terms was examined. Equations (3-57) and (3-58) consist of two components each, one corresponding to each of the stations involved in the equation. It was found that each of these components was approximately equal in magnitude to the other but opposite in sign, thus resulting in a very small element of A. This leads us to the conclusion that the solution is independent of these bias terms which means that these terms cannot be discriminated against the other parameters of the solution. Consequently, this solution was tried with errors with maximum standard deviations, σ_B, of $0^\circ.5$, $1^\circ.0$, and $2^\circ.0$. The results showed that errors of this magnitude have, absolutely, no effect on the position.

Next, another solution was tried with the weights for the lengths and the orthogonality parameters set to zero. Since it was apparent that the results might be dependent on the lengths of the baselines this solution was tried for two values of length, 1 and 50 m. The results are presented in Table 3-7.

TABLE 3-7. ACCURACY (1σ) OF DETERMINATION OF NONORTHOGONALITY (ϵ) AND BASELINE LENGTHS (L) PARAMETERS

Parameter	L = 1 m	L = 50 m
ϵ	69.1 arc-sec	1.4 arc-sec
L_1	0.02 cm	0.03 cm
L_2	0.02 cm	0.03 cm

From this table, it appears that the accuracy with which the nonorthogonality parameter can be determined is almost inversely proportional to the length of the baseline ($1 \times 69.1 \sim 50 \times 1.4$). On the other hand, even though the accuracy of the baseline lengths depends on the length of the lines, the decrease in accuracy is relatively small (50 percent decrease in accuracy for 5000 percent increase in length). This means that, for purposes of calibration, these lengths can be determined to the accuracy of 0.02 to 0.03 cm.

The capability of this mathematical model to recover the nonorthogonality parameter and the baseline lengths simultaneously may have very important consequences from the standpoint of the hardware requirements. Long baselines in the form of booms aboard a spacecraft have a tendency to sway and bend resulting in nonorthogonality and change of lengths in the baselines. Simultaneous determination of these parameters enables long baselines to be used in the interferometry system under study.

3.4.6 Effect of Position of the Unknown Station Relative to the Satellite Subpoint

In addition to the net of five stations given in Table 3-1, a fictitious point at the satellite subpoint is also used in this series of tests. Of these six stations, a group of five is used in each solution with the unknown station different in each case. This arrangement of stations gives a different geometrical configuration of the ground stations for each test. The results of four solutions obtained in this series of tests are presented in Table 3-8.

TABLE 3-8. EFFECT OF RELATIVE POSITION OF THE UNKNOWN STATION WITH RESPECT TO SATELLITE SUBPOINT ON POSITION ACCURACY (L = 1m, $\sigma_\gamma = 0°.25$)

Unknown Station	Distance From Subpoint (deg)	σ_H (km)	Increase in σ_H (%)
Subpoint	--	1.889	--
Quito	15	1.9880	5.2
Rosman	36	2.673	41.5
Natal	57	4.558	141.3

The results in the above table indicate that the position accuracy deteriorates as the unknown station is moved away from the subpoint. However, reasonable accuracy (within 40 to 50 percent) can be obtained for position of the unknown station within about 35° to 40° from the satellite subpoint.

3.4.7 Effect on Unknown Station Position Accuracy of a Priori Information on the Satellite Position

This aspect of the investigation was performed by including different values of a priori accuracy estimates in each solution. The effects of this variation on the unknown station position accuracy are shown in Table 3-9.

TABLE 3-9. EFFECT OF A PRIORI INFORMATION ON SATELLITE POSITION ON POSITION ACCURACY (L = 1m, $\sigma_V = 0°.25$)

Accuracy of Satellite Position (σ_{X_s}, σ_{Y_s}, σ_{Z_s}) (km)	σ_H (km)	Increase in σ_H (%)	A Posteriori Standard Deviation of Satellite Coordinates (km)		
			σ_{X_s}	σ_{Y_s}	σ_{Z_s}
0.1	1.988	--	0.1	0.099	0.1
1.0	1.989	0.05	0.998	0.989	0.999
10.0	2.080	4.1	9.1	5.89	9.7
100.0	2.861	43.7	26.8	10.6	37.7

These results show that any decrease from 10 km in the a priori accuracy estimate of the satellite position does not have any significant effect on the unknown station position. On the other hand, any increase from 10 km effects a substantial increase in the a posteriori standard deviation of both the satellite and the unknown station positions. This means that

(1) The satellite position cannot be determined accurately from the interferometry system alone

(2) Some type of a priori information on the satellite position is necessary for obtaining improved accuracy on the station position.

Any satellite in a geostationary orbit is not geostationary in the strictest sense. However, knowing the characteristics of its orbit (i.e., inclination, eccentricity, etc.) a table could easily be developed for its positions within 10-km accuracy which gives just about the highest accuracy in the station position. This makes it feasible to obtain good station positions without simultaneous tracking of the satellite.

Incidentally, the poor determination of the satellite positions from this system (interferometry) alone can be explained by the fact that the basic measurements made by this system are all angles. The condition expressed by the basic mathematical model as given in Equation (3-22) relates to the angle, at the satellite, between the directions to two ground stations. Owing to the very long distance between the satellite and the ground stations relative to the distances between ground stations, these three points (satellite and ground stations) will be near the critical sphere on which the angle will be the same for any position of the satellite. The closeness of these points to the critical sphere will only result in the horizontal components of the satellite position being poorly determined; but the radial component is poorly determined owing to the angle being very acute. However, it was found that this acuteness has, relatively, a smaller effect than the points being near the critical sphere. This may be noted in Table 3-9 which shows that the accuracy of the Y-coordinate is better than that of the X and Z coordinates since the Y-axis is close to the radial direction of the satellite purely by the choice of the satellite position (94° W longitude).

3.4.8 Effect of a Priori Information on the Lengths of the Baselines and on the Nonorthogonality Parameter

This effect is examined by comparing the results of two solutions where the lengths are assumed to be completely known in one, and in the other they are assumed to be completely unknown. The difference was found to be about 1.4 percent for a 1-m baseline and about 7 percent for a 50-m baseline which shows that the effect of variation in the baseline lengths on the position accuracy is very small. Hence, the lengths need not be considered as unknowns unless the baselines are boom type and extremely long. Similar results were also obtained for the nonorthogonality parameter. For moderate lengths of baselines, it is not very critical to consider these parameters as unknowns. In such circumstances, the unknown parameters are the two horizontal coordinates of the unknown station. Hence, only two reference stations are required to operate the interferometry system discussed in this report with moderate lengths of baselines. Such a test for a 50-m baseline showed only about 14 percent deterioration in the accuracy from the test with four reference stations.

3.4.9 Effect of Increased Accuracy of the Phase-Difference Measurements at the Reference Stations

It is considered possible that the condition under which these measurements are made can be controlled better at the reference station than at the unknown station. Some tests simulating this situation have been made and the results are presented in Table 3-10.

TABLE 3-10. EFFECT OF IMPROVED ACCURACY IN γ AT REFERENCE STATIONS ON POSITION ACCURACY (L = 1m)

σ_γ (ref. stn.)	σ_γ (unk. stn.)	σ_H (km)	$\sigma_H[\sigma_\gamma(\text{ref. stn.}) = \sigma_\gamma(\text{unk. stn.})]$
0°.25	0°.25	2.0	2.0
0°.25	0°.5	3.6	4.0
0°.25	1°.0	7.1	7.9

These results show that such improvement results in only about 10 percent improvement in the accuracy of the determination of the unknown station position. This means that every effort should be made for accurate measurement of γ for the unknown station to get the best possible accuracy in the station position.

3.4.10 Convergence of the Solution

The complexity of the mathematical model and the need for a priori values for most of the parameters have already been emphasized. Such values are readily available for all parameters except for the unknown station coordinates. How close these values must be to the true values are investigated in these tests. Several a priori values which correspond to different distances from the true position are assumed and the corresponding results are presented in Table 3-11. The accuracy set for the convergence is .01 m.

TABLE 3-11. NUMBER OF ITERATIONS REQUIRED FOR THE VARIOUS A PRIORI POSITIONS OF THE UNKNOWN STATIONS

A Priori Position Error (km)	Number of Iterations
0	0
100	1
300	3
1500	4

The computer time required for each solution is about 20 seconds and the time required for each additional iteration is negligible (<1 sec). Since a priori information on the station position is available to ≤ 1500 km, how close this information is to the true value is not very critical for the position determination.

4.0 SYSTEMS ANALYSIS: HARDWARE

It is possible to develop a number of navigation and/or surveillance concepts that can provide a variety of capabilities to a large number of users by modifying or changing the manner in which the elements of a basic interferometer system are apportioned among the user, the spacecraft, and the reference sites. An example of an interferometer which has been optimized for spacecraft attitude control is the ATS-6 configuration. The ATS-6 has been examined both analytically and experimentally by a number of investigators. It consists basically of a system in which a receiver in the spacecraft measures the signal phase difference between the interferometer receiving antennas and transmits these measured differences to a central ground site for processing. It has demonstrated a capability for measuring phase differences within an accuracy of 0.1 electrical degrees. The phase-measurement accuracy achievable is a function of the signal-to-noise ratio and numerous hardware parameters. In the experiments performed to date, transmitters with very large effective radiated power (ERP) have been used and thus the ATS-6 performance is not representative of the performance achievable for a navigation and/or surveillance system. The same basic system configuration can be adapted for use in navigation/surveillance applications. The ATS-6 hardware, however, is not capable of being practically adapted for these uses.

A brief review of the characteristics, hardware, and capabilities of the ATS-6 system, along with a description of some of the experiments which have been conducted with it, is presented immediately below. This review is followed by a description and brief discussion of a number of possible surveillance and/or navigation system concepts. Additional subsections consider the various sources that contribute to interferometer errors (independent of the specific concept); the requirements for the various parameters of an interferometer system and possible trade-offs; and the trade-offs, performance, and estimated costs for each of five candidate or "strawman" systems: surveillance/data collection; navigation/surveillance/data transfer (both low and high capability); aerial navigation/air traffic control/data transfer; and an "all purpose" or combination system.

4.1 ATS-6 Interferometer System

An interferometer system has been employed on the ATS-6 satellite primarily for attitude control. This system has been quite successful in providing precision attitude control data (Isley & Endres, 1975a and 1975b).

The ATS-6 interferometer consists of two orthogonal baselines 97.262 cm long for the fine or vernier phase measurement and two 8.105-cm baselines for the coarse phase measurement. Six horn antennas are used in an arrangement as shown in Figure 4-1. Two frequency channels were provided at 6.150 and 6.155 GHz corresponding to wavelengths of 4.878 and 4.874 cm, respectively. This provides a nominal baseline length of 19.95 λ for the vernier baseline and 1.66 λ for the coarse baseline. The antenna coverage is $\pm$ 17°.5, and the two baselines are oriented along the pitch (north) and roll (east) axes of the spacecraft.

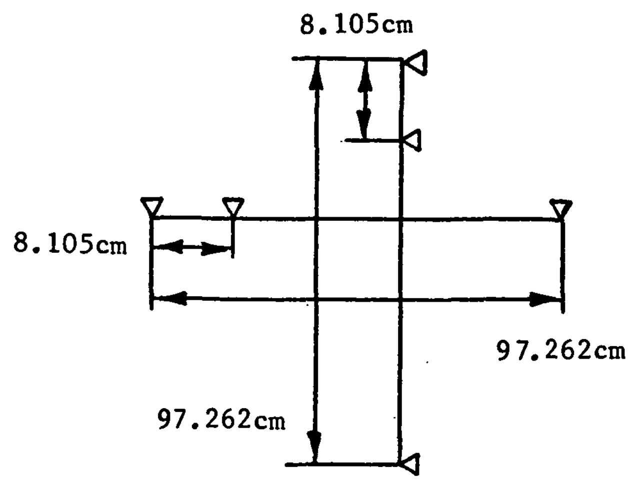


FIGURE 4-1. ATS-6 INTERFEROMETER BASELINE CONFIGURATION

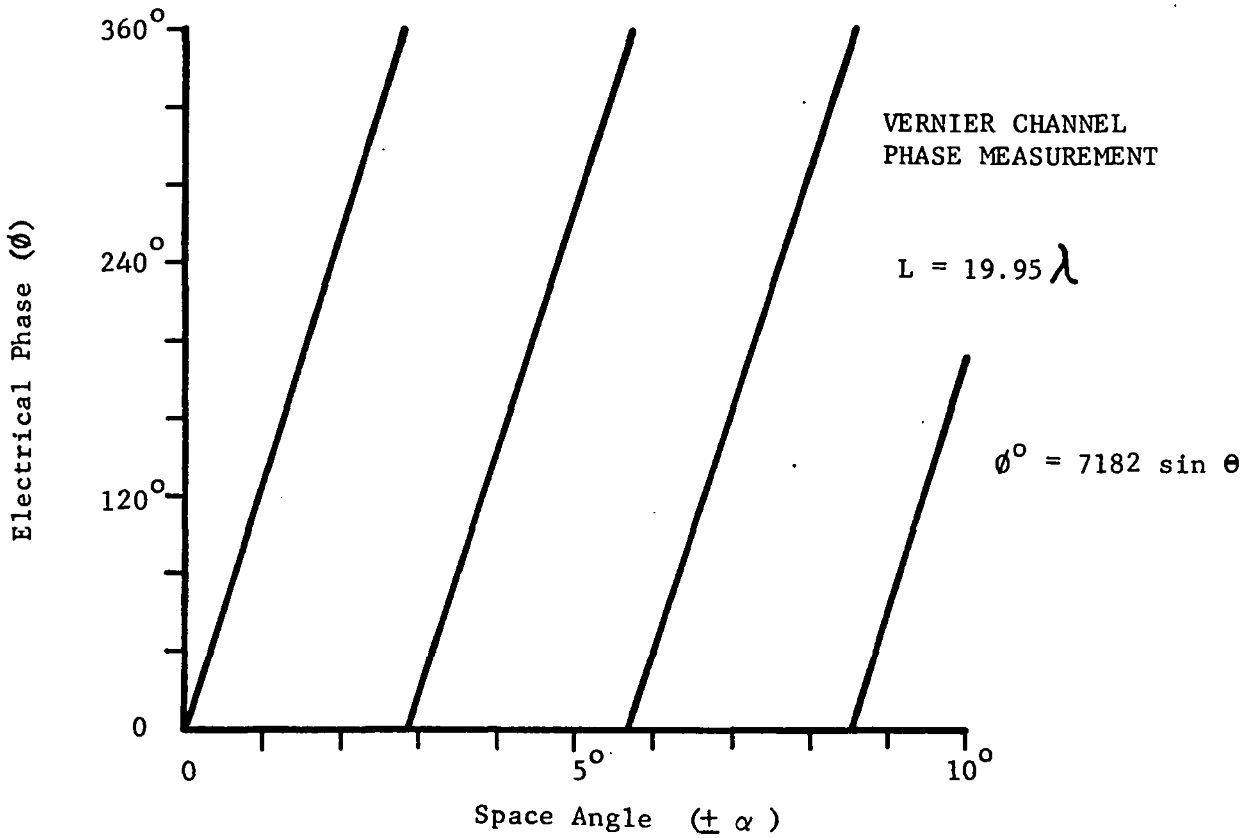
A space-angle resolution of 0°.0014 is provided, corresponding to a phase-angle resolution of 0°.176. This value is established by the spacecraft hardware configuration. An eleven-bit vernier data word is provided and a five-bit coarse word for each baseline and each frequency. The resolution of the coarse baseline is 1°.15 in space angle.

Since the phase angle is ambiguous every 2π radians, the vernier measurement is ambiguous every 2°.87. The coarse measurement has an unambiguous range of 37° which exceeds the antenna coverage zone. The vernier and coarse measurement capabilities of the ATS-6 interferometer are shown in Figure 4-2.

The spacecraft hardware configuration for the ATS-6 interferometer is sketched in Figure 4-3.

The six antennas are connected into a switching matrix (only two are shwon in the sketch) which serves three functions. It switches between coarse and vernier antennas to provide both the coarse and vernier measurements. It switches between roll and pitch antennas to provide measurements for both baselines, and it interchanges the reference antenna with the measurement antenna for calibration purposes.

Following the switching matrix is a filter and mixer in both the reference and measurement channels which coherently reduce the 6-GHz frequencies to 150-MHz. These mixers are fed by a common local oscillator and, in conjunction with the switching matrix and cabling, determine the noise figure for the receiver. The 150-MHz signal is amplified and fed to two more mixers which further coherently reduce the signal frequency to a nominal 30 MHz. The local oscillator frequencies for these two mixers have a 2-kHz offset which is generated by a phase-locked loop that is locked to a 2-kHz reference signal. The outputs of the mixers are summed to provide four frequencies at 27.5 and 27.498 MHz and 32.5 and 32.498 MHz corresponding to the 6.150- or 6.155-GHz signals. Two IF amplifiers at 27.5 and 32.5 MHz followed by square law detectors are used to separate the two input frequencies and to strip off the 2-kHz difference frequencies. The phase of this 2-kHz frequency relative to the 2-kHz reference is equal to the phase difference between the signals received at the two antennas. This is measured by a phase detector circuit which starts and stops a digital counter at the zero crossing points of the 2-kHz signals. This counter counts pulses from a 4.096-MHz master clock which is also divided down to provide the 2-kHz reference frequency. The output of the counter is directly proportional to the phase difference between the signals at the two antennas.



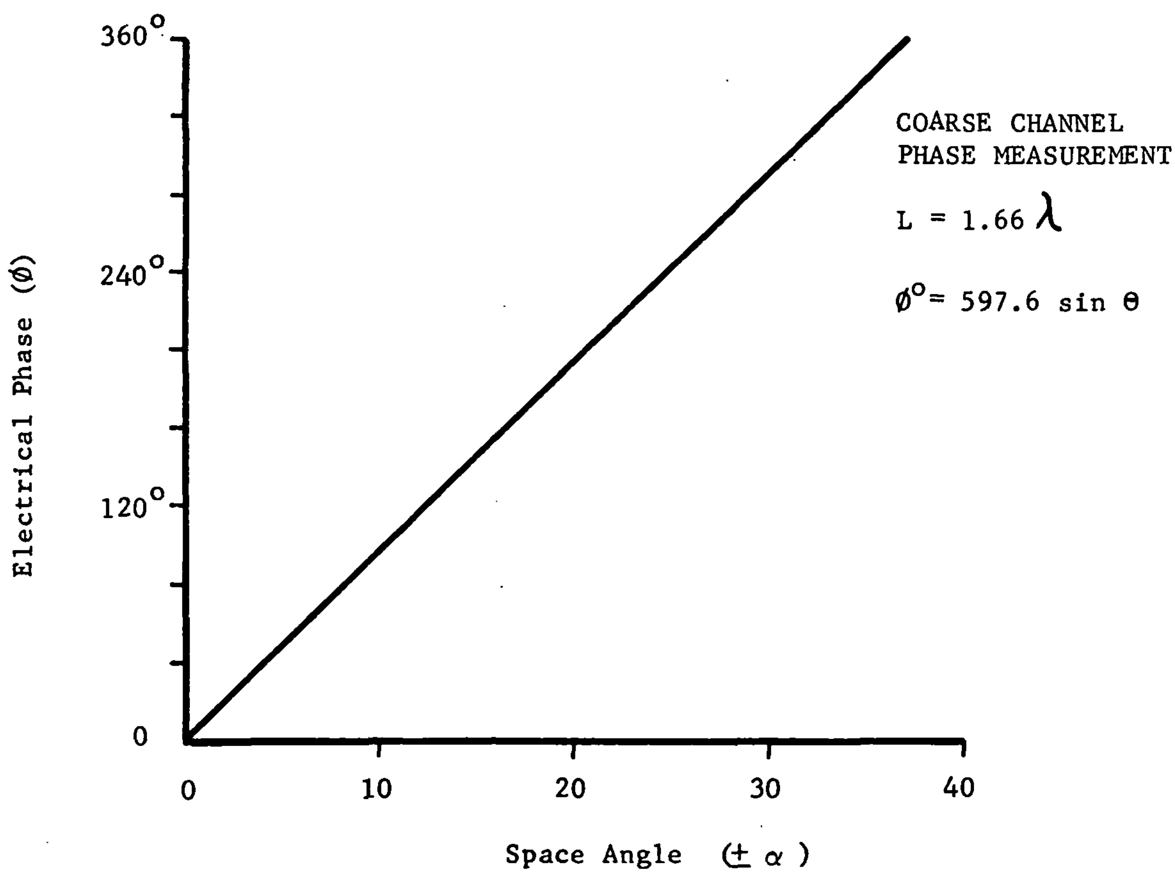


FIGURE 4-2. SPACE ANGLES VERSUS PHASE ANGLES FOR ATS-6 INTERFEROMETER

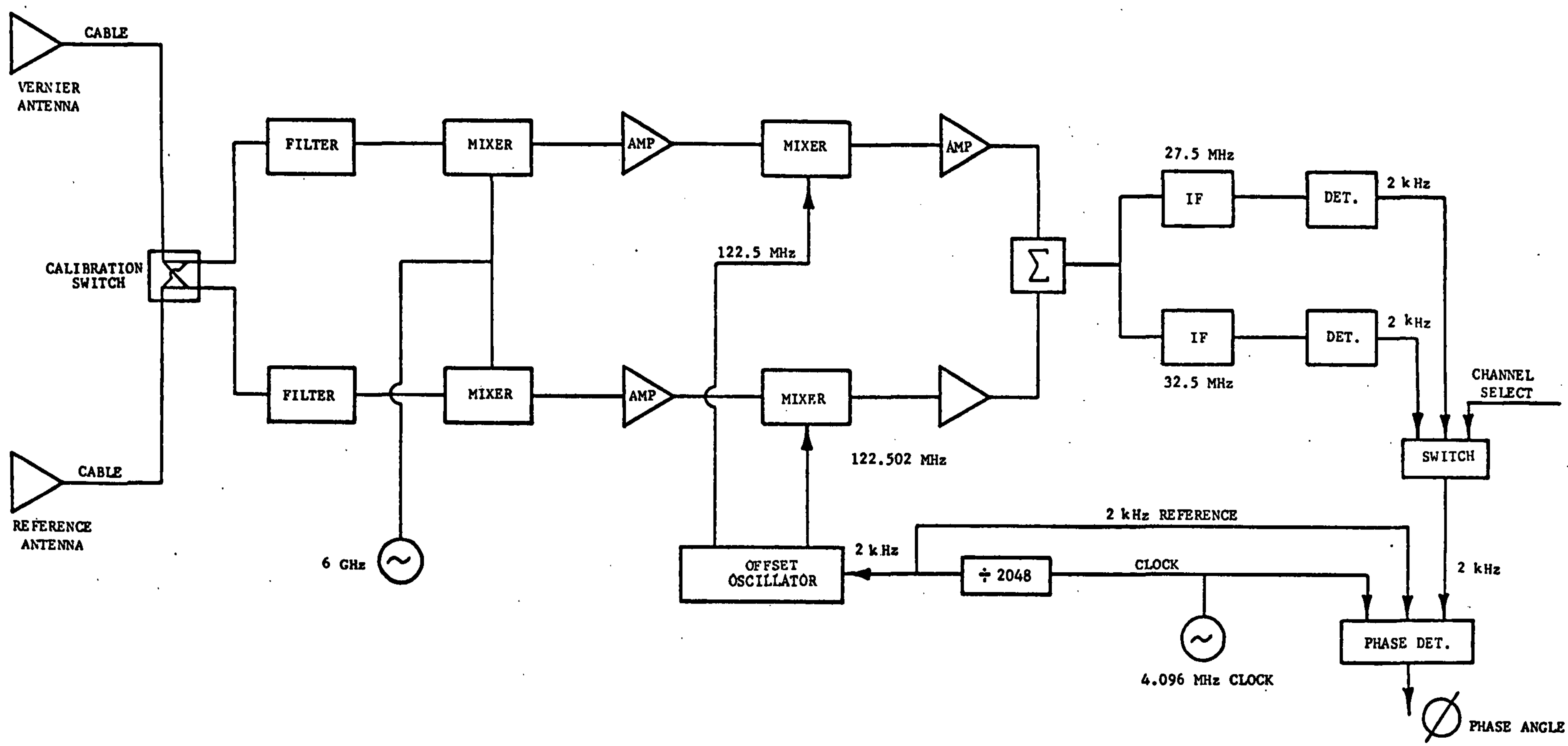


FIGURE 4-3. INTERFEROMETER BLOCK DIAGRAM OF VERNIER CHANNEL

The ground equipment consisted of two illuminators, one at Rosman, North Carolina, where a 26-m (85 ft) parabolic antenna and an 8-kw transmitter were used, and one at Mojave, California, where a 12-m (40 ft) parabolic antenna and an 8-kw transmitter were used. In addition, the interferometer measurements were transmitted to the ground from the spacecraft over a data channel using a 72-bit word every 3 seconds. The 72 bits included an 8-bit status word, 32 bits of phase data for the roll and pitch baselines at 6.150 GHz and 32 bits of phase data for the roll and pitch baselines at 6.155 GHz.

Experiments on the ATS-6 primarily involved using the interferometer as an attitude sensor for ground control of the spacecraft. This was designated the SAPPSAC (Spacecraft Attitude Precision Pointing and Slewing Adaptive Control) experiment. To determine attitude, both interferometer baselines must be used to determine the directions to two known illuminators. Shortly after launch, the 6.155-GHz channel failed, allowing only one illuminator at a time to be used with the interferometer. This required the use of another sensor in conjunction with the interferometer in order to determine the spacecraft's attitude. Both an earth sensor and a Polaris tracker were used with the interferometer during the experiments.

In calibrating the ATS-6 interferometer, bias errors in the phase measurements can be classified as those due to antennas and cabling preceding the switching matrix, those associated with the switching matrix, and those associated with the hardware following the switching matrix. Bias errors due to the switching matrix or the hardware following the switching matrix (with the exception of the phase-metering circuitry) can be determined by interchanging the antennas by means of the calibration switch. To determine the antenna and cabling bias errors, the spacecraft position was determined by ranging and compared with that determined by the interferometer and earth sensor. Matching these two positions provided estimates of the antenna and cabling bias errors.

The hardware configuration used for the ATS-6 interferometer was optimized to minimize the bias errors since uncalibrated bias errors would result in apparent attitude errors. The effective radiated power (ERP) available from the ground reference stations was quite high, so large postdetection signal-to-noise ratios were obtained resulting in a very low random error component. The observed data in general did not exhibit any significant noise until the signal levels dropped below a threshold value. Additional reductions in ERP of a few decibels resulted in complete signal loss.

For the ATS-6 interferometer, this point occurs within a few decibels of a unity predetection signal-to-noise ratio and this thresholding effect appears to be related to loss of AGC for signal-to-noise ratios below a few decibels.

The predetection bandwidths are relatively large for this system in order to minimize the bias errors. An interferometer optimized for navigation or positioning applications would require substantially smaller predetection bandwidths, with the resulting bias errors canceling during the data processing.

4.2 Possible Surveillance and/or Navigation Systems

4.2.1 Central-Site Processing Systems

An interferometer system which could provide a surveillance and navigation capability simultaneously typically would consist of a transmitter/receiver and antenna assembly for each user with an interferometer receiver, data transmitters, and multiplexing hardware on the spacecraft. The interferometer phase measurements could be made at the spacecraft or the interferometer signals could be relayed coherently to a central ground site where the phase measurements would be made and processed to determine user positions. For surveillance only, no receiver would be required by the user; for navigation, the processed position data would be relayed to the user through the satellite.

This system concept requires that all data processing to determine the positions of all users be accomplished at a central processing site. This requirement and the number of frequency channels available limit the number of users. In order for such a system to accommodate a large number of users, separate frequency channels as well as time slots must be provided. The channel bandwidths required are determined by the ground-transmitter frequency stability, the Doppler shifts resulting from either spacecraft motion or user motion, and the necessary information bandwidths if the same carrier is being used for both positioning and low-speed data transfer.

A system in which the spacecraft acts as a coherent relay (transparent satellite system) consists simply of a spacecraft receiver/transmitter which takes the coherent signals from a pair of orthogonal interferometer baselines and transmits them by means of coherent frequency multiplexing to a central ground receiving/processing site. This simplifies the spacecraft hardware in that channel filtering and phase measurements need not be carried out on-board. The penalty incurred is the requirement for both a coherent link of sufficient bandwidth to handle all of the sources that may be under simultaneous surveillance and, if the users also require position data for navigation or other purposes, a high-speed data link capable of transmitting the position data and user identification tags to the spacecraft. If the phase measurements were made on board the spacecraft, they could be telemetered back to a ground site for processing or, if no surveillance function were required, the processing could be carried out on board the spacecraft provided sufficient computational capability was available.

If a navigation or positioning capability is required in addition to surveillance, then the position data must be relayed from the spacecraft back to each user. This requires a low-speed data link with sufficient channels to accommodate the number of users.

With central-site processing the user transmitters could also be used to relay low-speed data to the central-processing site. This could be done with a system providing surveillance only as well as with a system providing both surveillance and navigation or positioning capability. Providing data-transfer capability of this type would probably reduce the number of possible different time slots that could be provided for such a system and might require dedicated frequency channels for the users relaying data if either continuous transmission or transmission of large quantities of data were required.

4.2.2 User Processing Systems

For a system providing only navigation data, the processing function can be carried out by each user, thus eliminating the requirement for a central processing site. In this case the spacecraft equipment consists of the interferometer receiver, phase meter, multiplexer, and transmitter. The user ground equipment consists of a transmitter, receiver, and micro/minicomputer to accomplish the data processing.

For a system of this type, the spacecraft could make the phase measurements for all the reference signals as well as the user signals. The use of a transparent-satellite approach in which the signals are coherently relayed to the user for the phase measurements would require a multichannel receiver and increase the cost of the user hardware. If the phase measurements are made by the spacecraft, then the measured phases along with timing, identification, and satellite ephemeris data could be transmitted back to the ground on the same frequency used by the ground transmitter.

The timing sequence for such a system could be the transmission of an identification and acquisition word by the potential user. If the channel is available, the spacecraft replies with a go-ahead signal and the user transmits an unmodulated carrier for the time required to accomplish the necessary phase measurement and then turns off. The spacecraft measures the received signal phases and, during the following time slot, transmits the measured phase data along with reference phase data, which are being measured essentially continuously at a higher data rate by the spacecraft, and the other data necessary for the user's computer to process the phase measurements into his position.

A system of this type cannot provide a surveillance capability or a data-transfer capability and may be slightly more expensive for the user since a computer would be required to process the phase data into position.

4.2.3 Inverted Interferometer System

Another navigation system concept which is quite different from that described above may be termed an "inverted" inferometer system. In such a system, the spacecraft carries an interferometer antenna array just as with the previous concepts, however, instead of receiving, the antenna array is used to transmit a different frequency from each antenna, all of which have been coherently derived from a common frequency source. On the ground, these frequencies are received and coherently translated to a common frequency for phase comparison and measurement. The spacecraft equipment for this concept is simply a transmitter, while the user equipment consists of a receiver and navigation computer.

Although this concept has not been examined extensively, it would have the advantages common to all systems in which the user requires only passive hardware, viz., unlimited number of users, relatively lower cost of equipment, and minimal frequency allocation requirements since no transmitter is required.

Several disadvantages also exist, of course. Since no reference stations are used, the spacecraft attitude must be known more precisely and phase bias errors resulting from spacecraft hardware will not be compensated for as they are with the previous concepts and must be controlled much more closely. In addition, such a system would not provide a surveillance or data-transfer capability and requires two satellites. Nevertheless, because of the advantages noted above, it should be examined in more detail.

The comparative differences and capabilities among the various concepts discussed above are summarized in Table 4-1.

4.3 Interferometer Error Sources

The performance of any interferometer system is highly dependent upon the manner in which the phase difference is measured. Classically, optical interferometers function simply by summing the outputs of the two elements. Most radiofrequency interferometers measure the phase differences directly. Since the signal levels at the antennas are very small, they require amplification prior to any phase measurement. If an accurate phase-difference measurement is to result, only known phase shifts should be introduced in the signal path from any one antenna not present in the others. This means the phase shifts introduced by the antennas must be the same, that the cables connecting the antennas to the amplifying electronics must be of known and constant length, the phase shifts produced by the electronics prior to the phase-measuring circuitry must be equal and constant with frequency and temperature.

For a satellite-based interferometer, the signal phases can be measured on-board the satellite, such as with the ATS-6 interferometer, or they can be retransmitted to the ground using a coherent transponder and the phase measurements made on the ground. Either approach can be successful, although the cost

TABLE 4-1. *INTERFEROMETER SYSTEM CONCEPT COMPARISONS*

Concept	Application Modes	User Equipment Requirements	Spacecraft Equipment Requirements	Limitations	Advantages
Central-Site Processing	Surveillance/ and data collection	Transmitter	Interferometer receiver	Requires large central computer and high-speed one or two-way data link from central site to spacecraft; spacecraft hardware is expensive	Moderate user equipment cost, largest number of applications
	Navigation	Transmitter and receiver	Two data-link transmitters and receivers; one high speed, one low speed		
	Data transfer/ traffic control	Transmitter and receiver	Two data-link transmitters and receivers; one high speed, one low speed		
User Processing (Conventional)	Navigation	Transmitter, receiver, and computer	Interferometer receiver and low-speed data transmitter	No surveillance or data-transfer capability; higher cost user equipment	Lower spacecraft cost; no central processing site required
User Processing (Inverse)	Navigation	Receiver and computer	Interferometer transmitter	No surveillance or data-transfer capabilities; two satellites required	Unlimited number of users, lowest user equipment cost

distribution between ground and spacecraft hardware and central-site processing is different in the two cases.

For an interferometer positioning system, only those hardware errors which are dependent upon the angle of the transmitting stations relative to the interferometer antenna boresight are important in influencing the location of an unknown transmitter. Other errors, common to both the reference and unknown stations, cancel during the processing for the position of the unknown stations since all measurements are relative to the reference station positions. Thus, most bias errors in the phase measurements are not critical to an interferometer positioning system; only frequency-dependent differential biases which cannot be removed by either calibration of the hardware or by cancellation during the processing for the unknown station position are critical.

4.3.1 Phase Measurement

The major source of error in the phase measurement process is associated with random noise on the signal. For a digital phase measurement, the random phase error associated with noise is given by $1/\sqrt{SNR}$ where SNR is the signal-to-noise power ratio. This assumes the noise statistics are gaussian, which is true for thermal noise. Figure 4-4 illustrates the magnitude of the noise-produced random-phase error as a function of the ground-transmitting antenna diameter for several transmitter power outputs (P_o) and receiver integration times (T). The system parameters used to compute this error are given on the figure. For most system concepts, the random phase error due to system noise will be the dominant source of unknown station position errors.

4.3.2 Hardware

There are a number of potential phase-error sources associated with a specific interferometer hardware configuration. Of these, only those which can contribute a differential phase bias which is dependent upon the transmitting station position are significant for a navigation system. These can be divided into errors associated with the interferometer antennas and those caused by the rest of the hardware.

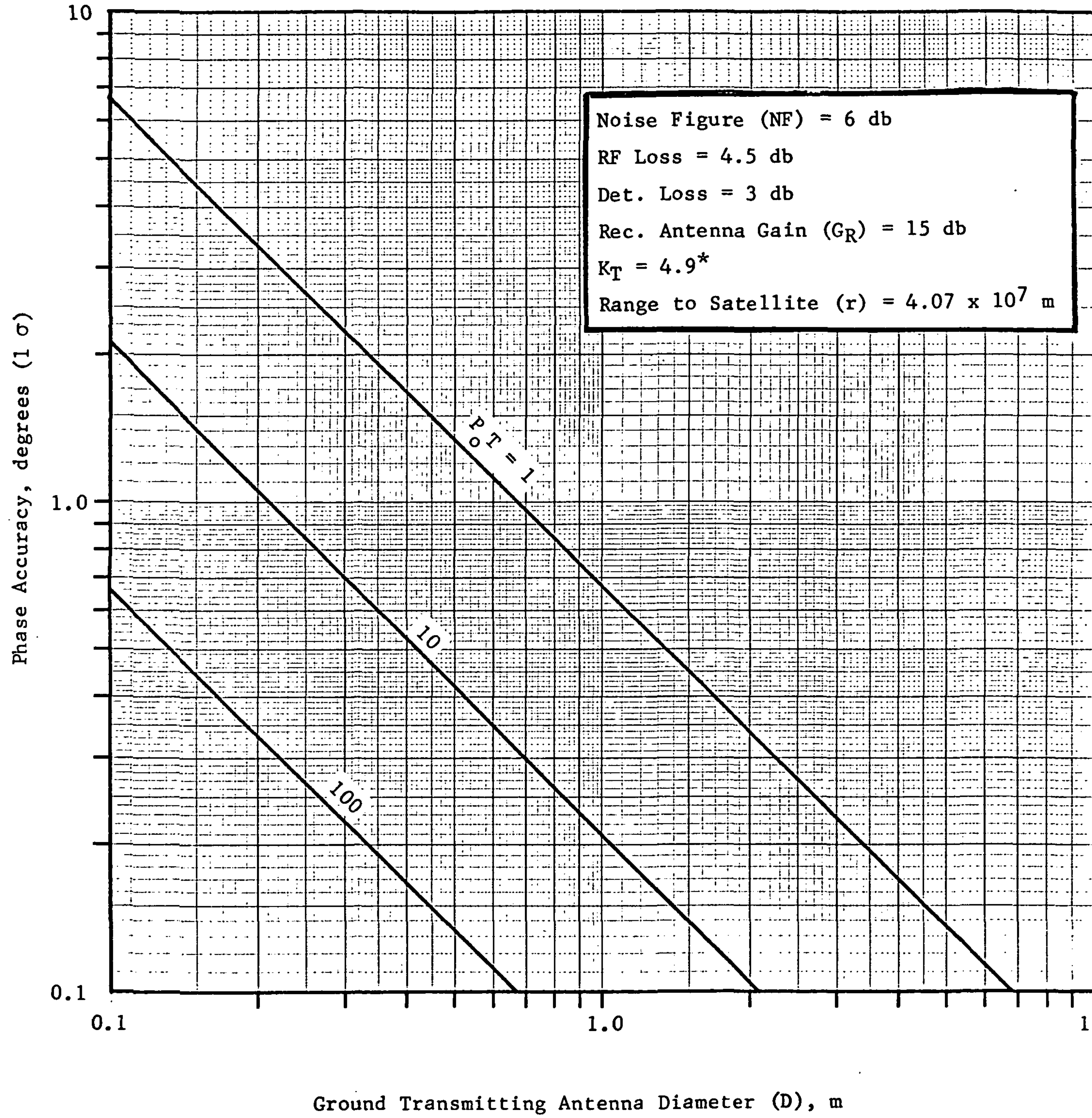


FIGURE 4-4. PHASE ERROR VERSUS GROUND ANTENNA SIZE

* K_T is defined in Equation 4-12.

The antennas can contribute several sources of error. One of these is due to polarization mismatch between the transmitted signal and the interferometer receiving antennas. If both the ground transmitting antennas and the interferometer-receiving antennas are circularly polarized, errors due to this cause will be less than 0.1 electrical degree. Other factors of importance with respect to the interferometer antennas are a minimum phase center shift over the antenna beamwidth with angle and with frequency and the tracking of the phase centers of both antennas with both angle and frequency. Similarly, the antenna polarizations should be highly circular and the polarization ellipses of both antennas should track with angle and frequency. In addition, the mutual coupling between antennas must be minimized. The mutual coupling causes a phase error that varies over the antenna field of view. The maximum error produced is $\Delta\phi \approx 2\sqrt{C}$ where C is the mutual coupling between the antennas. To keep this error below 0.1 degree requires a coupling of less than -55 decibels.

Other instrumentation or hardware errors result from instabilities in the receiver oscillators, cross-talk between the receiving channels, and non-linearities or saturation in the receiver. Other than antenna or RF cable-related errors such as those due to differential thermal expansion of a partially illuminated array, the major hardware error source is due to frequency-dependent phase shifts produced by the receiver filters. Ideally, the filters should have a constant time delay versus frequency which gives a linear phase shift versus frequency response. Filters having a linear phase response and also a narrow bandwidth with sharp skirts are very difficult to build. Generally a compromise solution must be used. In addition, temperature variations will affect the phase shift produced by a filter. The amount of phase shift per degree of temperature change will generally be proportional to the ratio of the filter center frequency and the filter bandwidth. The proportionality constant is a function of the specific details of the filter construction and components. Again, a filter with a very narrow bandwidth and a high center frequency will be very sensitive to temperature variations. The most important criterion is, of course, the extent to which the filters in the interferometer channels track in phase due to variations of either temperature, frequency, or signal amplitude.

For digital phase meters, another source of phase error is the quantization noise. This has a standard deviation of the order of $\sqrt{2/3}\ \pi$ radians referenced to the phase-meter clock frequency. The quantization error can be reduced by using a higher frequency clock and should not be a significant error source for an interferometer system.

4.3.3 Boom Motion

One of the obvious sources of errors in an interferometer system results from any change in the orientation or separation distance of the interferometer antenna array. If the antennas are mounted on long booms which extend beyond the primary structure of the spacecraft, such as would be required in order to achieve very long baselines, then any expansion or contraction, twist, vibration, etc., in these booms can result in interferometer position errors. As verified by the analysis of Section 3, changes in the baseline length and orientation can be determined and corrected for during the data processing and they do not result in significant errors, provided they occur sufficiently slowly that they can be considered constant during the integration period.

In general, thermal effects occur slowly and thus are easily compensated for by the above process. Twist of the boom or deflections which result in relative rotation of the antenna pointing directions must be minimized in order to maintain the antennas pointing to within 1° to 2° of the zenith. An analysis of these effects on a crossed array consisting of two orthogonal 75-m (246 ft) booms by Tsitsera, et al. (1973) indicates antenna rotation and misalignment errors to be less than ±1° due to thermal effects on the spacecraft. Shorter booms should, of course, be even better.

Boom vibrations which result in motion of the interferometer antennas can be calibrated out if the angular rates at which the tips are moving are sufficiently low. The requirements on the reference signal integration times required to accomplish this will be discussed subsequently.

In general, although there appears to be a reluctance on the part of many individuals to believe that large booms can be effectively used with a satellite interferometer system, analysis indicates that antenna booms up to the order of 100 m in length will not be the source of major errors.

4.3.4 Multipath

For ground-based users, there will be essentially no multipath error contribution. For airborne users, however, the multipath error can be a significant component of the total system error budget and cannot be removed by the data processing as can most of the system bias errors. In general, the multipath error increases with aircraft altitude, and with decreasing elevation angle, while it decreases with aircraft velocity, integration time, and frequency.

Detailed calculation of the specific multipath error is quite difficult since it depends upon the terrain characteristics in the vicinity of the user as well as a number of geometric factors and antenna characteristics such as the sidelobe levels and polarization. A worst-case type of analysis can be made, however, in which the effective differences in the space angle between the direct ray from the user and the average multipath ray are obtained. From the geometry for a geostationary satellite, the space-angle difference is given as

$$\Delta\theta \approx 4.468 \times 10^{-5} h \text{ radian} , \tag{4-1}$$

where h is the user height in kilometers. This represents a worst-case condition for an elevation angle of 30° and decreases to zero for increasing elevation angles. This space angle results in an electrical phase difference of

$$\Delta\gamma \approx \frac{2\pi L}{\lambda} \times 4.468 \times 10^{-5} h \text{ radian} . \tag{4-2}$$

The maximum phase-measurement error resulting from this is given by

$$\sigma\gamma_{max} \approx 2\sqrt{\frac{M'}{ST}}\sqrt{\frac{1}{2}(1 - \cos\Delta\gamma)} \quad , \qquad (4\text{-}3)$$

where M' is the total multipath reflected power in the signal channel and S is the total signal power. The multipath power is spread over a bandwidth determined largely by the effective roughness height correlation length, the user velocity, and the wavelength. An estimate of the multipath bandwidth for an average surface is

$$B \approx \frac{0.154V}{\lambda} \quad , \qquad (4\text{-}4)$$

where V is the user velocity in meters/second and λ is wavelength in meters. The phase-measurement error then becomes

$$\sigma_{\gamma_{max}} \approx 2\sqrt{\frac{M\lambda}{0.308\ SV\ T}}\sqrt{1 - \cos\left(\frac{2\pi L}{\lambda} \times 4.468 \times 10^{-5} h\right)} \quad . \qquad (4\text{-}5)$$

In this expression S is the total signal power, M the total multipath power, V the user velocity, T the measurement integration time, and λ the interferometer wavelength.

The resulting position error using the same one-dimensional model used previously is

$$\sigma_x \approx \frac{\lambda r}{\pi L \sin\epsilon}\sqrt{\frac{M\lambda}{0.154SVT}}\sqrt{\frac{1}{2}\left(1 - \cos 2.8 \times 10^{-4}\frac{L}{\lambda}h\right)} \quad . \qquad (4\text{-}6)$$

As an example, consider an aircraft flying at an altitude of 6 km, with a velocity of 250 m/sec. If the interferometer has a baseline of 50 m and a wavelength of 5 cm is used, then for an integration time of 1 sec, and an M/S ratio of - 30 db, the resulting error is of the order of 50 m. Figure 4-5 illustrates the multipath error versus the signal-to-multipath power ratio.

In general, the above analysis is valid if the multipath is largely the result of diffuse reflections as will be the case for a 6-GHz wavelength. At lower frequencies, and over some types of terrain, a dominant specular reflection

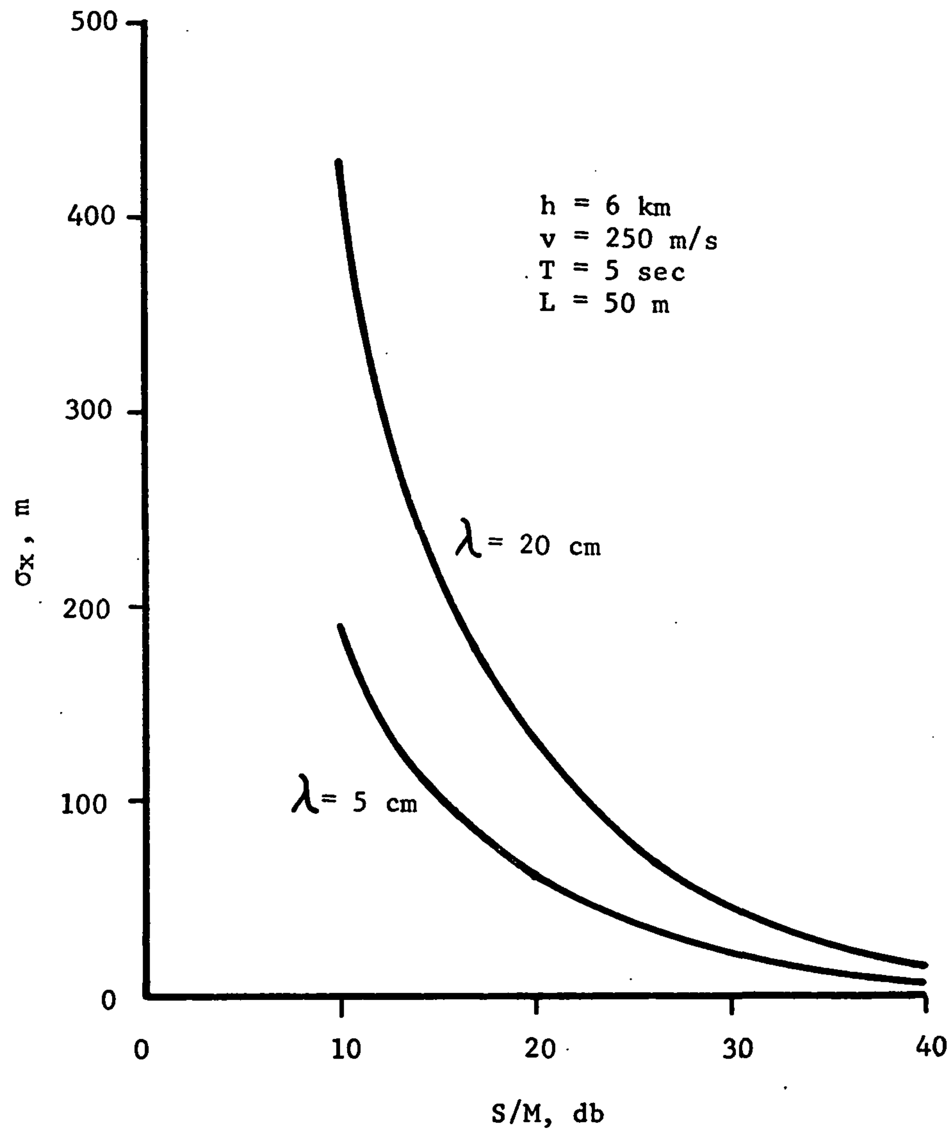


FIGURE 4-5. MULTIPATH ERROR VERSUS SIGNAL TO MULTIPATH POWER RATIO

may exist, in which case the error will increase. The actual multipath errors encountered for an interferometer system by airborne users will need to be determined experimentally in most cases.

4.3.5 Interference

Interfering signals also present a potential source of error. For an interfering signal in the receiver passband which is lower in level than the desired signal a phase error will be produced in the phase measurement process. A sinusoidal carrier will result in a phase error of

$$\sigma_{\gamma} \approx \frac{2}{\sqrt{2\pi \Delta f S/I}} \quad , \tag{4-7}$$

where S/I is the signal-to-interference power ratio and Δf is the frequency separation in Hertz. Noiselike interference will result in errors similar to those produced by the system random noise.

For interference outside the receiver passband which is very large compared to the desired signal, the performance of an interferometer will depend strongly upon the hardware configuration used. If a phase-locked loop system is used in order to track doppler variations in the received signal then a sufficiently large signal outside the nominal passband of the phase-locked loop can cause the loop to unlock. Under these circumstances no position information would be obtained.

4.3.6 Atmospheric

The major effects of the atmosphere are to produce refraction of the signal as it passes through the trophosphere and ionosphere. The troposphere will, in general, deflect the signal toward the earth while the ionosphere will result in a S-shaped bend in the ray path. The actual angular error resulting from these effects depends upon the elevation-angle and the frequency, with the frequency dependence being produced by the ionosphere. In addition, the error is a function of the time of year, time of day, location on the earth, and climatic conditions. For frequencies above 1 GHz, the errors due to ionospheric effects will be less than 0.01 mrad for elevation angles above 15°.

The major error source then is due to tropospheric refraction. The use of an appropriate refraction model in the data processing will allow corrections to be made for most of the refraction error. The remaining error then will be due to unmodeled effects which generally vary slowly with time. In order to minimize these effects, the reference stations used in the solution for an unknown station should be located near the coverage limits for a particular spacecraft, this is an elevation angle in the 20° to 30° range if possible. Some feeling for the standard deviation in elevation angle resulting from tropospheric refraction effects is given in Figure 4-6. This figure illustrates several sets of computed curves for various climatic conditions. The curves B, C, D, G, and E were calculated from various sets of radiosonde refractive index profile measurements made at several locations and at different times (Bauer, et al., 1958; Fannin and Jehn, 1957). Curve F represents experimental observations made from Hawaii (Beam, et al., 1960). The cross represents a different set of experimental measurements. From these data it appears that maximum angle errors of the order of 0.1 mrad can result if the elevation angle is restricted to 15° or above.

The rapid fluctuations in the angle of arrival of the signal due to turbulent irregularities of the refractive index in the atmosphere are another source of angular error. In general these cannot be corrected for. Typical errors due to this source for elevation angles above 15° can amount to 0.05 mrad.

Thus, in order to avoid excessive errors, the operating frequency in general should be above 1 GHz, and the elevation angle should be above 15°. If frequencies in excess of about 8 GHz are used, the signal loss due to atmospheric water-vapor absorption becomes significant and frequencies above 8 GHz should, in general, be avoided.

4.4 System Parameter Selection

The specific system parameters required by an interferometer positioning system are a strong function of the system application. A number of trade-offs exist with respect to the system accuracies, number of users, data rates, hardware costs, etc. A number of these parameter trade-offs are discussed below.

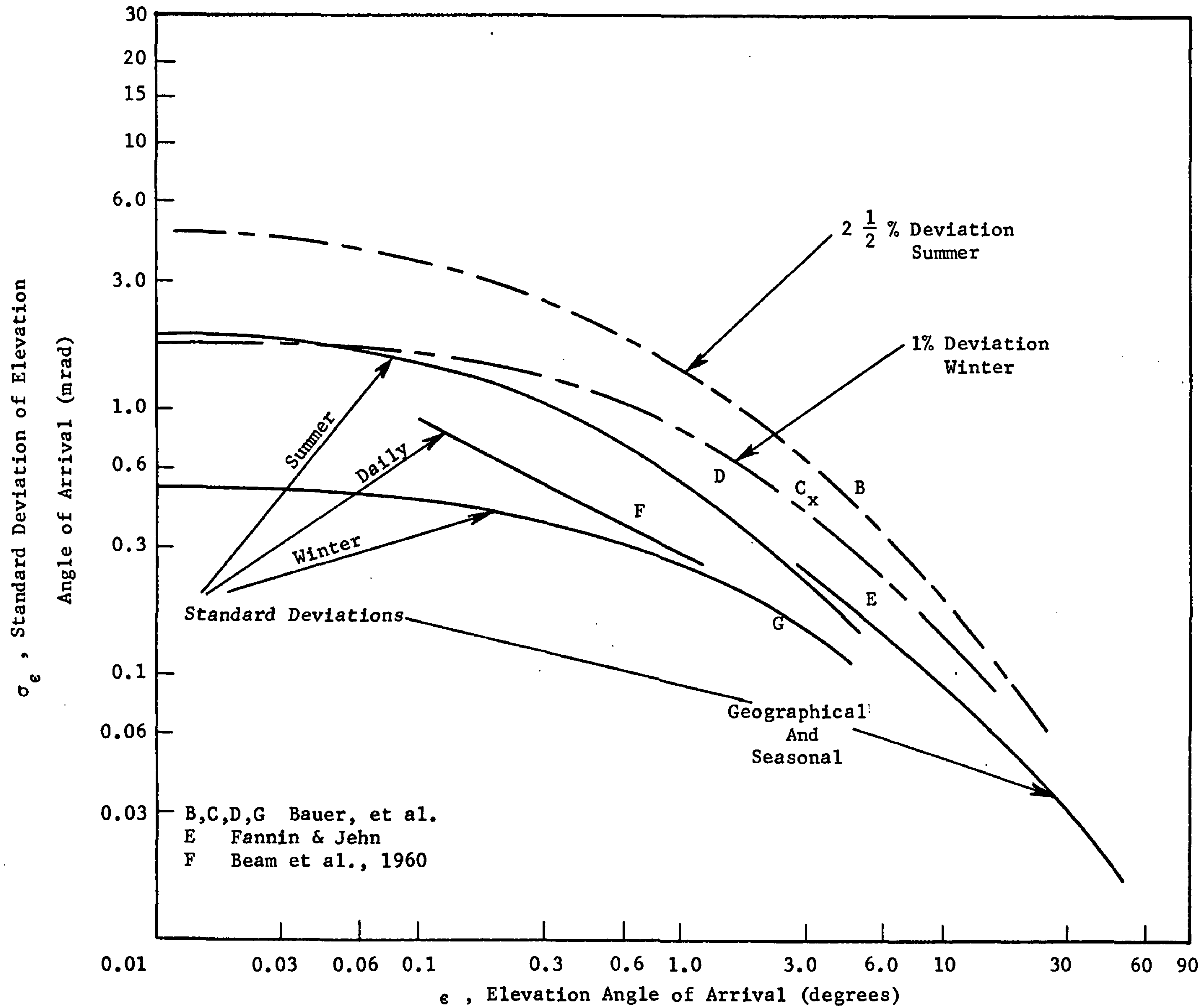


FIGURE 4-6. SLOWLY VARYING UNCORRECTED REFRACTION ERRORS

4.4.1 Operating Frequency

The constraints on the choice of operating frequency for an interferometer system are imposed by atmospheric effects, hardware capabilities, and positioning-accuracy considerations. The operating frequency should be high enough that ionospheric phase shifts and refraction errors due to passage of the signal through the ionosphere are not significant, and low enough that atmosphere losses due to water-vapor and oxygen absorption are not significant. This bounds the possible operating frequency range between about 1 and 8 GHz. Within this range, the achievable accuracy for a given interferometer baseline length is approximately a linear function of the operating frequency. This can be demonstrated as follows:

For a geostationary satellite interferometer system the approximate linear error in position due to a given phase error can be estimated using a one-dimensional model as

$$\sigma_x \approx \sigma_\gamma \frac{\lambda}{2\pi L} \frac{r}{\sin\varepsilon} \left[1 - \left(\frac{R}{h}\right)^2 \cos^2\varepsilon\right]^{1/2} \tag{4-8}$$

where h is the satellite's altitude measured relative to the earth's center, r is the range from the unknown transmitter to the spacecraft, ε is the elevation angle of the spacecraft relative to the local horizontal at the unknown transmitter, R is the radius of the earth, λ is the wavelength, L is the interferometer baseline length, σ_γ is the standard deviation in the phase measurement, and σ_x is the standard deviation in position.

If a small angle approximation is used, which is appropriate for the present discussion, then

$$\sigma_x \approx \sigma_\gamma \left(\frac{\lambda}{2\pi L}\right)\left(\frac{r}{\sin\varepsilon}\right) . \tag{4-9}$$

Now the phase error is related to the post-detection signal-to-noise ratio as indicated previously by

$$\sigma_\gamma = \frac{1}{\sqrt{S/N}} . \tag{4-10}$$

The signal-to-noise ratio is given by

$$S/N = \frac{P_o G_T G_R \lambda^2 T}{(4\pi r)^2 N L_s} \quad , \tag{4-11}$$

where P_o is the transmitter power output, G_T the transmitter antenna gain, G_R the receiving antenna gain, T the integration time, N the system noise power, and L_s the system loss including cabling, RF switches, etc. The noise power N can be written as kT_oNF with NF the receiver noise figure, and $kT_o \approx 4 \times 10^{-21}$. The transmitting antenna gain can be written as

$$G_T = K_T \, D^2/\lambda^2 \quad , \tag{4-12}$$

where D is the antenna diameter for a parabolic dish or an effective maximum linear dimension for other antenna types. The coefficient K_T is a function of the specific antenna type and for a parabolic dish is approximately 4.9.

Using these expressions, the signal-to-noise ratio becomes

$$S/N = \frac{K_T P_o D^2 G_R T}{(4\pi)^2 r^2 kT_o NFL_s} \quad , \tag{4-13}$$

and

$$\sigma_x = \frac{2r^2\lambda}{LD\sin\varepsilon} \approx \sqrt{\frac{kT_o \; NF \; L_s}{K_T P_o T G_R}} \quad , \tag{4-14}$$

The receiving antenna gain is, of course, for a given antenna a function of frequency. However, the primary requirement on the receiving antenna is a beam-width sufficiently large to provide coverage of the entire earth while still providing some gain. Since the gain of an antenna is proportional to the product of the principal plane half-power beamwidths essentially independent of the wavelength, this fixes the receiving antenna gain. Thus the accuracy can be written as

$$\sigma_x \approx \frac{\lambda}{LD\sin\varepsilon} \; K_e \sqrt{\frac{NF \; L_s}{P_o T}} \quad , \tag{4-15}$$

where

$$K_e = 2r^2\sqrt{\frac{KT_o}{K_T G_R}}$$

is a constant independent of the operating frequency, baseline length, transmitting antenna diameter, elevation angle, receiver noise figure, losses, or power output and integration time. Since the noise figure and system losses are only weakly frequency dependent, particularly in the frequency range from 1 to 8 GHz, the linear dependence of the L/λ ratio dominates.

This indicates that, in general, for a given baseline length as high a frequency as possible should be used until either increases in the achievable noise figure or system losses due to atmospheric effects begin to dominate. Other considerations such as frequency allocations and hardware availability, data rates, power output, and cost versus frequency also influence the operating frequency choice, of course.

The relationship indicated in Equation (4-15) can be clearly demonstrated by plotting the position accuracy σ_x versus the transmitting antenna diameter for various P_oT ratios and a parameter $L' = \frac{L\sin\varepsilon}{\lambda}$. Curves are presented in Figure 4-7 for a system where G_R = 15 db, NF = 6 db, L_s = 4.5 db, K_T = 6.5 db, and a 3-db detector loss is included. This represents a conservative set of parameters believed to be easily achievable anywhere in the 1 to 8-GHz frequency range. In fact, at the lower end of this range, noise figures of the order of 3 db are achievable and the total system losses should not exceed 2 to 3 db.

It should be noted that the accuracies determined by the above analysis are in agreement with those determined by the rigorous methods of Section 3 if the random noise component is the dominating error. For systems in which the random-noise error component is of the same order as other system error contributions, then the analysis methods of Section 3 must be used to determine the overall system accuracy.

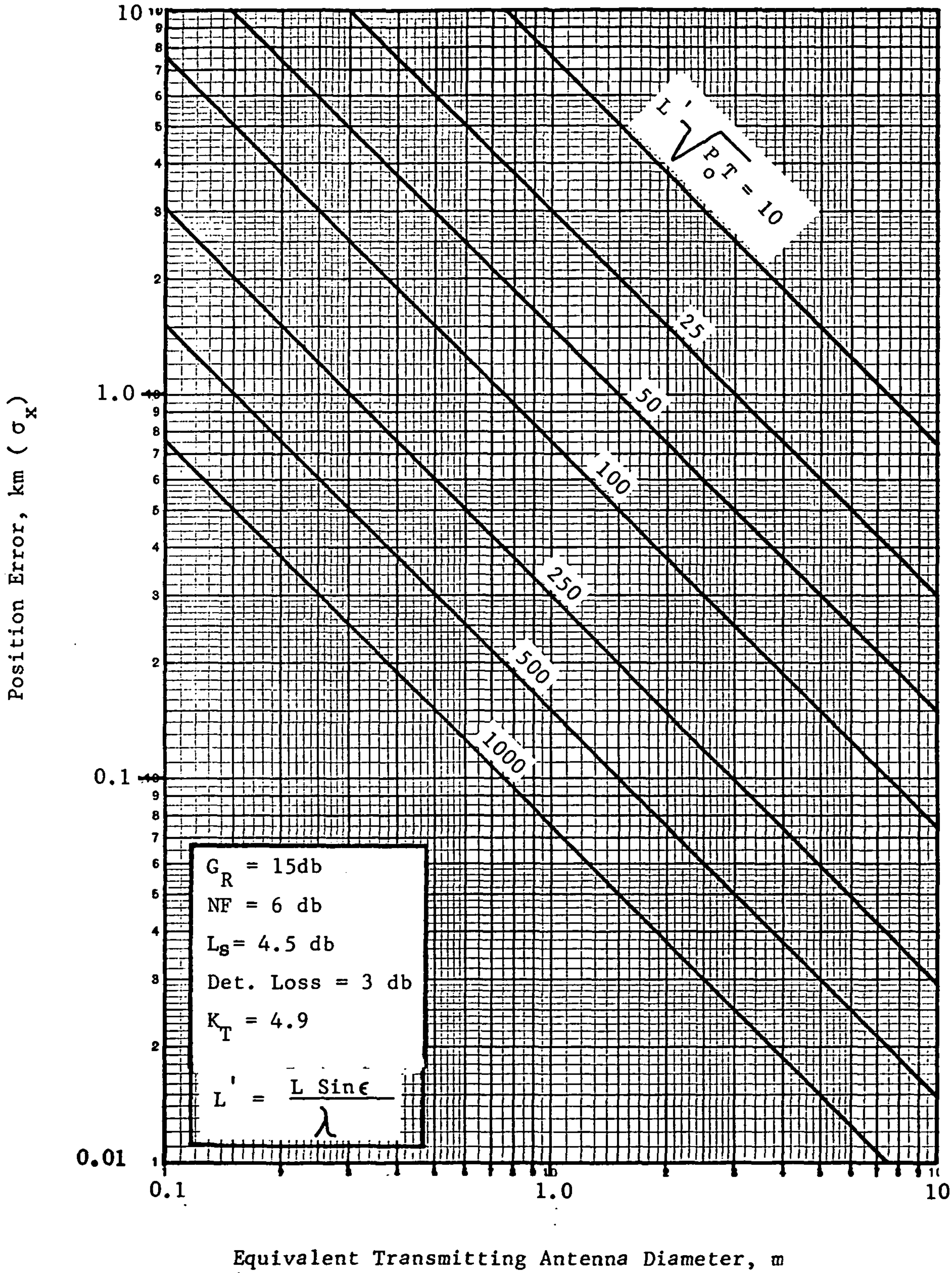


FIGURE 4-7. POSITION ACCURACY VERSUS GROUND ANTENNA DIAMETER

4.4.2 Ground Station Effective Radiated Power

The effective radiated power (ERP) requirement for a user ground station is dictated primarily by several considerations. The first and most stringent of these is a cost and physical size constraint on the user antenna. A large antenna, although providing high gain and thus greater ERP for a given transmitter power output, is extremely expensive, difficult to control and point with the required accuracy and, in many cases, simply physically too large to be accommodated by most potential users. These factors all tend to drive the antenna size and gain downward and, in general, the smallest antenna capable of satisfying the system accuracy and data-rate requirements should be used.

From a transmitting standpoint, sufficient ERP is required to provide the postdetection signal-to-noise ratio necessary to obtain the desired accuracy. The curves of Figure 4-7 illustrate the trade-offs that exist among transmitter power output, integration time, antenna size, electrical baseline length, and system accuracy. Although these data were calculated using a very simple one-dimensional model for the accuracy estimates, the results are in essential agreement with those of the more sophisticated analysis of Section 3 and the trade-offs are the same.

A significant requirement for the ground-station antenna is the need for maintaining the antenna main lobe pointed at the spacecraft under whatever conditions exist with respect to the receiver motion. For a large high-gain antenna, this requires a stabilized antenna mount or a steerable beam for a moving platform. On the other hand, if a sufficiently wide antenna beamwidth can be used, a stabilized platform or beam steering will not be required with a resulting substantial decrease in the cost of the ground equipment. For example at 1.6 GHz, a 30-cm (1 ft) dish has a half-power beamwidth of about 27°, this would appear to be barely sufficient to insure acquisition of the spacecraft if manual pointing is used.

It would be advantageous if no antenna pointing at all were required. In this event the user transmitting antenna would require a wide vertical beamwidth of the order of 160° between half-power points centered on the zenith. The gain of such an antenna would be of the order of a few decibels at most. Reduction of the transmitting antenna size and resulting ERP could be compensated for insofar as the positioning accuracy is concerned by an increased interferometer baseline. An additional requirement on the transmitter ERP, however, is to provide a sufficient predetection carrier-to-noise ratio to activate the AGC circuitry if an ATS-6-type interferometer receiver is used or a sufficient carrier-to-noise ratio to provide the required bit error rate for data transmission. Figure 4-8 illustrates the IF carrier-to-noise ratio versus transmitting antenna diameter as a function of the power output to IF bandwidth ratio for the system. If a phase-locked loop-type receiver is used, then the bandwidth represents either the acquisition bandwidth or the loop bandwidth. Regardless of the specific receiver implementation, sufficient predetection bandwidth is required to activate the IF AGC loop, allow signal acquisition, and provide an adequate bit error rate for data relay.

In order to minimize user equipment costs, the same ground antenna would probably be used for receiving as well as transmitting. In this case the antenna gain should be consistent with the down-link carrier-to-noise requirements for the system bit error rate for those systems incorporating navigation or positioning capabilities.

For example, if a data rate of 75 bps is used with a differentially coherent phase-shift-keyed modulation, then to provide an error rate of less than one bit per hour requires an error probability of less than 3×10^{-6}. This requires a predetection signal-to-noise ratio of approximately 13 db. If a channel bandwidth of 250 Hz is used to accommodate the modulated signal plus a vehicle motion of about 27 km/hr (15 knots), then for a 30-cm antenna a power output per channel of about 0.25 w would be required to provide the 13-db signal-to-noise ratio. For the ground transmitter, this would present no difficulty since only one channel is required.

For the receiving case where information is being transmitted to the user from the spacecraft, a per channel power requirement of 0.25 w could limit the total number of user frequency channels available because of the total power output limits on the spacecraft transmitter.

The trade-offs with respect to the number of users, available channels, and channel bandwidths will be discussed further in the following sections.

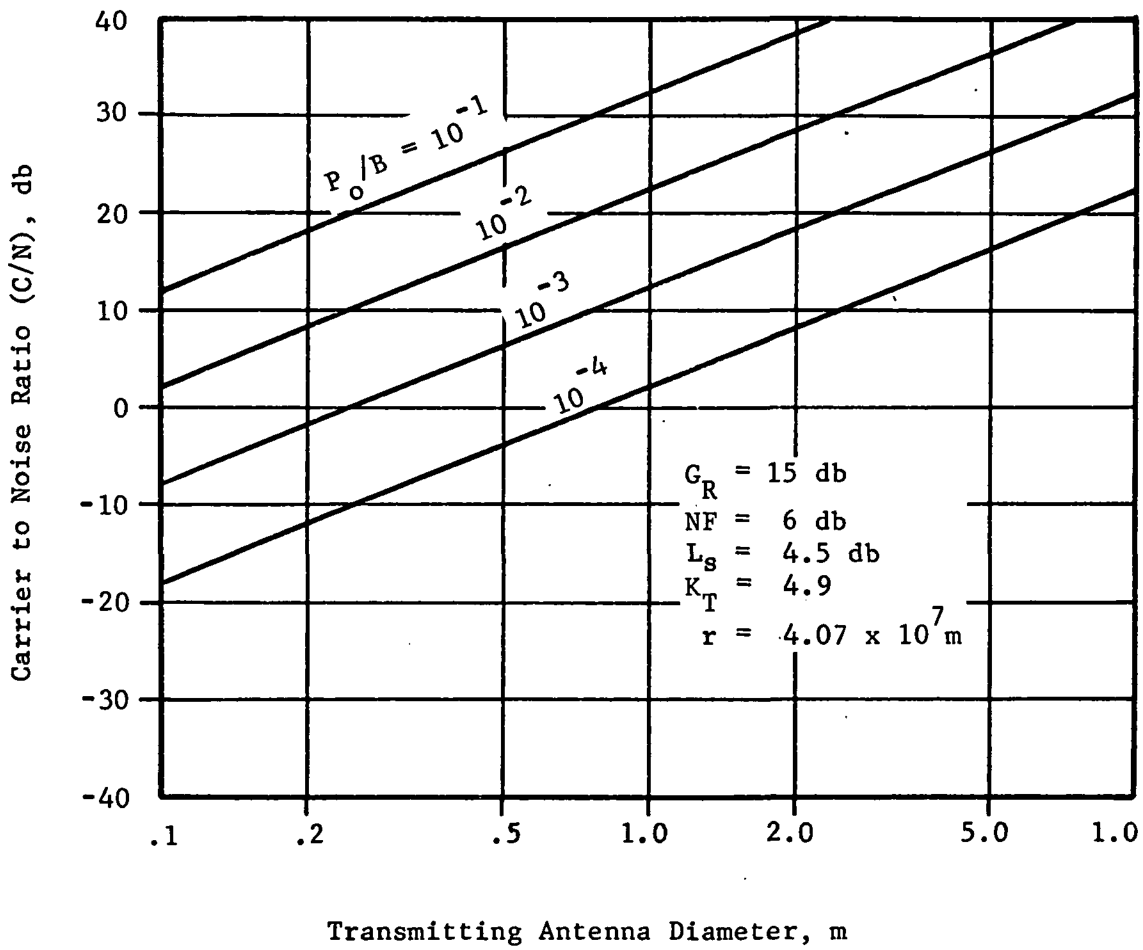


FIGURE 4-8. PREDETECTION CARRIER-TO-NOISE RATIO

4.4.3 Channel Bandwidths

The required predetection channel bandwidths are determined by the need to accommodate the data modulation bandwidths, the expected variation in the signal frequency due to ground transmitter drift and Doppler shifts, and the specific hardware implementation for the interferometer receiver. The bandwidth requirements due to data modulation are generally small if the data rates are low. Doppler shifts can range from about 40 Hz for a 10 m/sec user velocity at 1.6 GHz to 4 kHz for a 200 m/sec user velocity at 6 GHz.

The ground-transmitter drift rates depend upon the frequency stability of the ground transmitter and for a stability of 1 part in 10^7 at 6 GHz amount to 600 Hz. Poorer stability would, of course, result in larger frequency drifts. Because of the deleterious effects of increased channel bandwidths on the ground antenna sizes and both ground and spacecraft transmitter power outputs, the limiting factor on the channel bandwidths should be the modulation bandwidths and hardware requirements. In general it will be much less expensive to provide increased frequency stability in the ground transmitters than to increase the antenna size or the transmitter power outputs.

Variable Doppler shifts or transmitter frequency shifts can be accommodated by the use of phase-locked loop tracking filters; however, sufficient signal-to-noise ratio must be provided to allow loop acquisition to occur. This presents a particularly severe requirement when aircraft platforms are being used. The high Dopplers present on a signal transmitted from an aircraft requires either a wide acquisition bandwidth if a comb filter or spectrum analyzer is used, resulting in a high ERP requirement on the ground transmitter, or, if sweeping phase-locked loops are used, an increase in the acquisition time.

The postacquisition bandwidth is determined primarily by the data rates and the multipath spreading since both transmitter drifts and Doppler shifts can be tracked by phase-locked loops if the rates are not too high.

4.4.4 Integration Time Requirements

The effective integration time used in the phase-measurement process influences the system accuracy through its effect on the signal-to-noise ratio as illustrated in Figure 4-7. In addition it has a significant influence on the number of users a system can handle and on the accuracy with which velocity can be measured by an interferometer system.

Since the reference transmitters can use much larger antennas and higher power transmitters than the users, the ERP's for the reference signals can be much larger than for the user's signals and shorter integration times can be used to provide the same or better accuracies. The need for relatively short integration times for the reference signals is determined by the requirement for removing the effects of baseline nonorthogonality and length changes. If large baselines are used requiring the spacecraft antennas to be installed on long booms, then the effects of thermal expansion and contraction of the booms as well as boom vibration can be compensated for if the integration times for the reference signal phase measurements are sufficiently short that no appreciable antenna motion occurs during the integration period.

An analysis of the effects of boom motion reveals that for large booms the largest effects are due to the maximum angular rate at which the antennas at the boom tips are moving and a phase error of

$$\Delta\gamma \approx \frac{2\pi L}{\lambda} W_B T \tag{4-16}$$

is produced where W_B is the angular rate of boom motion and T is the integration time. The integration time for the reference signals must be sufficiently short that $\Delta\gamma$ is less than the error produced by the signal-to-noise ratio of the reference signal. In general, small amplitude vibrational motion of the booms produces phase errors much less than those resulting from boom dip displacements caused by thermal-expansion and -contraction effects.

For the user signals, longer integration times will increase the effective signal-to-noise ratios and thus the positioning accuracy or will allow reductions in the transmitter power output, transmitter antenna diameter, or baseline lengths for the same accuracy. On the other hand, long integration times will reduce the velocity-measurement capability since the velocity must be determined from the changing position fixes with time.

Similarly using longer integration times will reduce the number of users that can be accommodated since the time allocated to obtain a position measurement for a given user must increase.

4.4.5 Number of Potential Users

The requirements imposed on the spacecraft hardware by the number of potential users vary depending upon the operational mode. For a system in which the phase measurements are accomplished at the spacecraft, a number of users can be accommodated by the use of both frequency and time multiplexing. A number of frequency channels can be provided and users accessed either sequentially or randomly within each frequency channel. Random operation would allow access at any time; however, conflicts could result and erroneous data be produced if time overlap occurs. Sequential operation would allow essentially clear channel usage by each user. This could be accomplished either by interrogation from the spacecraft or by the use of fixed time slots which are assigned to each user. For those users who are also transferring data over the interferometer link, the time requirements would be much greater than for positioning alone and if an essentially continuous data relay or a continuous position update capability is required, dedicated frequency channels would be necessary.

For a surveillance system or emergency monitoring system, it appears that both random time and frequency assignments would maximize the number of users for a given band of allocated frequencies. For navigation and position location or air-traffic-control applications, the number of potential users depends upon the specific data rate and accuracy requirements, and assigned frequency channels and time slots would appear to be required.

A system providing air traffic control or navigation capability would generally be limited in the number of users by spacecraft transmitter power requirements. For example, if a comb filter or sweeping phase-locked loop is used for signal acquisition with a maximum data rate of 100 bps, then a loop bandwidth of 100 Hz is adequate to accommodate the modulation. The transmitting/receiving antenna on an aircraft cannot be steerable, in general, and thus will be low in gain and have a broad beamwidth. For a gain of 2 db, at 1.6 GHz, the transmitter power requirement to provide a 13-db carrier-to-noise ratio for a 100-Hz channel is 3.3 w per channel, assuming a 3-db NF, 3 db RF system loss, and a 15-db transmitting antenna gain. Thus for a 100-w total spacecraft transmitter power output only 30 frequency channels could be provided. The number of available channels would decrease if higher frequencies were used.

The use of a multiple steerable beam antenna on the spacecraft would alleviate the limitations on the number of users imposed by the data relay requirements to some extent since increased transmitting antenna gains could be obtained. Such antennas are not operationally available at this time, however, and would present some difficulties with user acquisition in angle.

Similarly, the use of a steerable phased-array antenna which would permit the user to track the spacecraft would allow significant increases in the ground antenna gain and would, in general, alleviate the limitations on the number of users. Such an antenna might, however, be expensive and does not represent currently available hardware.

4.4.6 Data-Transfer Capabilities

Two requirements exist with respect to data transfer between the spacecraft and a user for an interferometer system. For a surveillance system, data will need to be relayed from the user station to the spacecraft. In the simplest case this may be merely an identification number, or it may be desired that sensor or other data be relayed essentially continuously from the user site to the spacecraft for further transmission to a central processing site.

For a system which has positioning or navigation capabilities, it will be necessary for data to be transmitted from the spacecraft to the user station. This would consist of the user's position if the processing is done at the spacecraft or a central ground site, or satellite ephemeris and timing information as well as the multiplexed coherent signals from the interferometer antennas if the phase measurement is being made by the user.

In both cases, it is desirable to maintain the rate of data transmission as low as possible consistent with the system requirements in order to minimize the channel bandwidth requirements, the ground-equipment costs, and the spacecraft-transmitter power requirements. Obviously data could be transmitted on a separate channel from the one being used for the position measurement signal. This is generally undesirable, however, in that it would increase the frequency allocation requirements and the ground equipment costs. Thus it is of interest to explore the capabilities for data transfer that exist using the measurement channel either simultaneously with the position measurement or in a time multiplex mode.

As indicated previously, there is a strong coupling between the data rate requirements reflected in the channel bandwidths and the required power output per channel from the spacecraft down-link transmitter. For the up-link, the requirements are not as severe since only one channel is involved and all the available power lies in this channel. Thus the maximum attainable data rate is determined by limitations on the spacecraft transmitter power output if there are a number of users and by the phase errors produced by the modulation if data are transferred during the measurement process. For a surveillance system, only the ground-equipment requirements need to be considered since data will not be transferred from the spacecraft to the users. For navigation applications, the spacecraft must transfer data to a number of users essentially simultaneously and sufficient transmitter power must be available to provide the required bit error rate.

If the interferometer carrier is modulated in order to relay data during the measurement process, then the resulting phase error in the measurement process will be highly dependent upon the modulation technique and the specific hardware implementation of the detection and phase-measurement process.

During a study conducted by IBM for NASA (Tsitsera, et al., 1973) measurements were made of the phase errors produced by biphase modulation of the interferometer carrier at rates of 10 and 20 bps. The primary result of this was a change in the mean phase angle measured with no significant increase in the standard deviation of the phase measurement. The mean phase change averaged 0.73 electrical degree for the 10-bps data and 1.5 electrical degrees for the 20-bps data. This error is undoubtedly associated with the attempts of the phase-meter circuits to measure phase during the phase reversal periods. Techniques are available to recreate a reference carrier which has had a phase shift modulation stripped from it and which is phase-locked to one of the two possible phase states. This could then feed a phase-measurement circuit to provide phase measurements which are essentially free of errors produced by the data modulation.

There are two major considerations in the choice of modulation to be used for the relay of data from the user station to the spacecraft. If the data are to be transmitted simultaneously with the phase-measurement carrier, then it should have a minimum effect on the phase measurement, and whatever modulation is used should result in a minimum bit error rate for a given carrier-to-noise ratio and should require a minimum channel bandwidth. With respect to compatibility with the phase-measurement process the use of a biphase modulation should result in essentially no phase measurement error if a suitable phase-measurement technique is used. Figure 4-9 compares the bit error rate with the predetection signal-to-noise ratio for a number of modulation techniques. Of these the use of coherent phase modulation provides the best performance, while a differentially coherent phase modulation is only slightly poorer. Thus, it appears that a differentially coherent biphase shift keyed modulation represents the optimum for interferometer data transfer applications. The bandwidth requirements in this case are also minimal and equal the data rate.

If a phase-shift coded modulation which is optimum for this application is used, it is felt that hardware techniques exist which would not result in significant errors in the phase-measurement process. This leaves the effects of the required channel bandwidth on the number of users and ERP requirements of both the user ground stations and the spacecraft as the limiting factors on the available data rates. Figure 4-10 illustrates the trade-offs between the channel bandwidths and the transmitter power output per channel for various antenna gains and frequencies of 1.5 and 6 GHz. These data apply to either an up-link or down-link, in general, although slight differences in the receiver-system noise temperature exist in the two cases. The spacecraft antenna is assumed to have a gain of 15 db for either transmitting or receiving. It is apparent that for a low-gain user antenna very large transmitter powers are required per channel if large channel bandwidths are used.

4.5 "Strawman" System Trade-Offs, Performance, and Costs

To illustrate somewhat more specifically the type of performance available from interferometer systems for the particular applications under consideration in this study and the costs that might be anticipated in their development, a

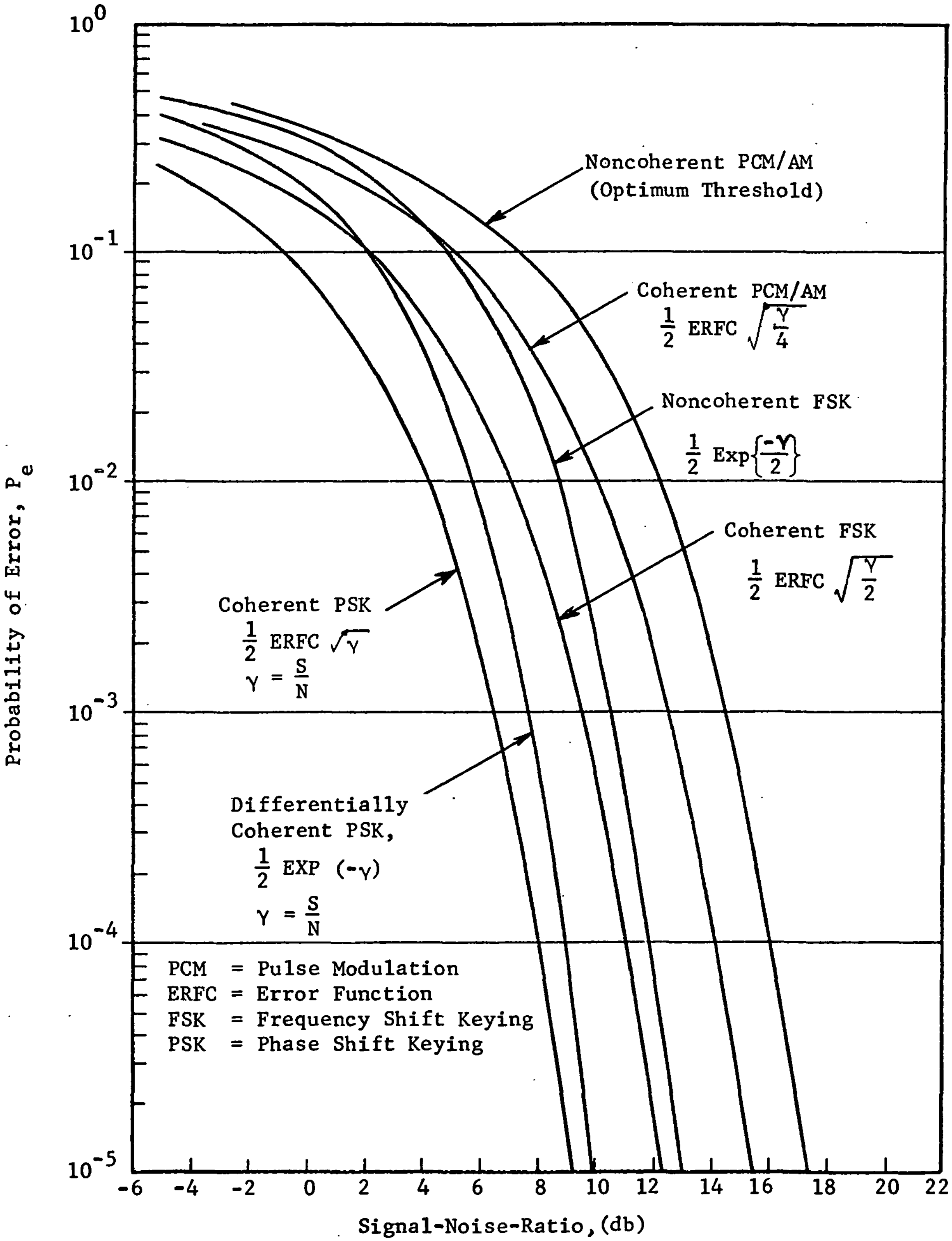


FIGURE 4-9. ERROR RATES FOR VARIOUS PULSE CODE MODULATION TECHNIQUES

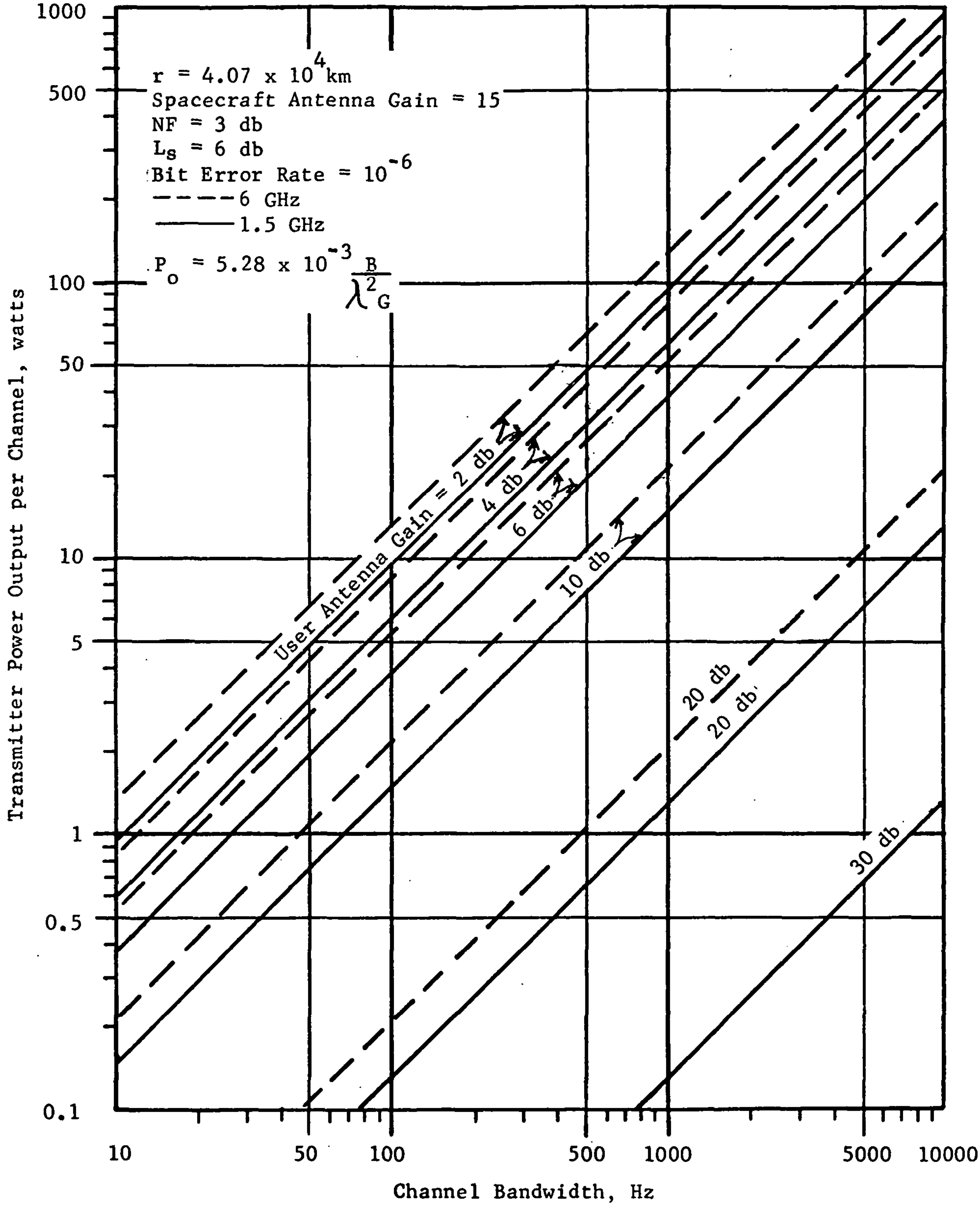


FIGURE 4-10. TRANSMITTER POWER OUTPUT VERSUS CHANNEL BANDWIDTH REQUIREMENTS

discussion of five "strawman" or candidate systems is presented in this subsection: surveillance/data collection; navigation/surveillance/data transfer (low and high capability); aerial navigation/air traffic control/data transfer; and "all purpose" or combination. However, before proceeding with the discussion of these systems, a general discussion of the various trade-offs which can be considered in the development of the candidate systems is given. The estimated performance of these systems is based on a simple one-dimensional model for the errors; however, this represents, in general, an upper bound on the errors determined using the rigorous methods of Section 3.

4.5.1 System Tradeoffs

Consider a transparent satellite system with central-site processing using antenna booms of the order of 50 m in length. If a frequency in the vicinity of 6 GHz is used, at an elevation angle of 15°, the parameter $L \sin \varepsilon/\lambda \approx 260$ and for a P_oT product of 10, an antenna gain of 13 db would result in a positioning error of about 500 m. This corresponds to a 10-cm horn or equivalent antenna. From Figure 4-11 this 10-cm horn would have approximately a 23° half-power beamwidth which would require at least manual pointing at the spacecraft.

For an antenna gain of 13 db, Figure 4-10 illustrates that a power output of 0.1 w per channel is required. For a 10-Hz channel a 1-w transmitter would be more than adequate. If a 10-w transmitter is used, then 1-kHz of bandwidth is available allowing approximately 1000-bps data rates.

Going down in frequency would allow the data rate to increase in proportion to the inverse square of the frequency if the same transmitter power output and integration times are used while the accuracy will decrease in direct proportion to the reduction in frequency. Thus, if a frequency of 1.5 GHz is used, then for a 1-w transmitter the antenna gain can be reduced to increase the beamwidth and avoid the requirement for antenna pointing. If a 3-db antenna gain is used with a 1-w transmitter then a 15-Hz channel bandwidth can be used. The reduction in frequency by a factor of 4 would result in a reduction in the effective gain of the ground antenna by a factor of 16, or 12 db, if the antenna size were to remain the same. Thus, to obtain the 3-db antenna gain at 1.5 GHz, an aperture only slightly larger than the 10 cm used at 6 GHz would be satisfactory.

In this event the positioning accuracy would be proportional to the frequency reduction and would decrease to 2.0 km if all other system parameters were constant. Actually the lower frequency would result in lower RF system losses at the interferometer and a receiver noise figure much better than 6 db. It is expected that 3 to 6-db improvement in system performance could result giving an accuracy of approximately 0.5 to 1.0 km.

Thus, for surveillance applications with limited data-transmission capabilities, a ground system operating near 1.5 GHz with a transmitter power output of 1 w could provide a positioning accuracy of about 1 km and a data rate of 10 bps.

For systems in which no antenna steerability is available, a major constraint is to maintain sufficient antenna beamwidth that the spacecraft is illuminated regardless of the specific position of the user. This requires near-hemispherical coverage and restricts the ground antenna gains to relatively low values (of the order of 2 to 4 db). If this is imposed as a major system constraint, then for a given transmitter power output, bit error rate, and interferometer baseline length, a trade-off exists between the positioning accuracy, data rate, and operating frequency. For fixed baseline length and transmitter and receiver antenna gains such as would be the case, the position accuracy is independent of the frequency and depends only on the postdetection integration time. The maximum useful data rate, on the other hand, is proportional to the square of the wavelength and thus indicates that as low a frequency as possible should be used consistent with avoiding atmospheric or ionospheric errors. This implies an operating frequency in the 1-GHz region.

For a system where a steerable antenna mount is available, such as for use on a ship for navigation, a different set of system constraints exists. A high-gain ground antenna can be used, in which case the physical antenna size, coupled with the pointing accuracy requirements, imposes a fixed size limit on the antenna and the performance illustrated in Figure 4-7 exists with respect to positioning accuracy. In this case the maximum data rate is essentially independent of the operating frequency and as high a frequency as practical should be chosen in order to give as large an electrical baseline length as possible. This results in increased accuracy in positioning. It will be necessary, however, to be able to maintain the antenna pointing accuracy and may require a tracking antenna mount.

Choosing two example systems, consider a 1-m parabolic antenna for the ground station. At 6 GHz, a 50-m baseline is 1000 electrical wavelengths long. From Figure 4-7, accuracies of the order of 100 m are obtainable with a power-integration time product of 1. From Figure 4-8, a 1-m antenna would need a power-predetection bandwidth ratio of about 5×10^{-4} to give the 13-db predetection signal-to-noise ratio required for a 10^{-6} bit error rate. Thus if a 1-w power output is provided, a data rate of 2000 bps would be possible for a 1-sec post-detection integration time.

Figure 4-11 indicates that the dish has a half-power beamwidth of about 2°.5. In general, it would be necessary to use a tracking antenna mount with such a system in order to maintain the satellite within the mainlobe of the antenna.

If a dish or horn of about 15 cm (6 in.) diameter is used at 6 GHz, then from Figure 4-11 the beamwidth is about 15° and a simple antenna mount combined with manual acquisition and steering or perhaps a simple mechanical steering mechanism should suffice. In this case, the accuracy becomes about 200 m for the 50-m baseline and the data rate drops to about 55 bps for the same 1-w power output. If there is a trade-off between power output and integration time, then the data rate can be increased while maintaining the same system accuracy.

4.5.2 Hardware Requirements and Estimated Costs

The overall hardware specifications for each of the five candidate or "strawman" systems, along with the estimated costs for the user ground equipment, are given below. Table 4-2 provides a summary of these specifications and costs. All of these systems are based on the use of a 50-m interferometer baseline on a geostationary spacecraft. The reasons for selection of this baseline length are these: booms with lengths of this order are being considered by NASA for a disaster warning satellite, a good candidate as a platform for an interferometer positioning-system experiment; and such lengths should be readily attainable and allow an

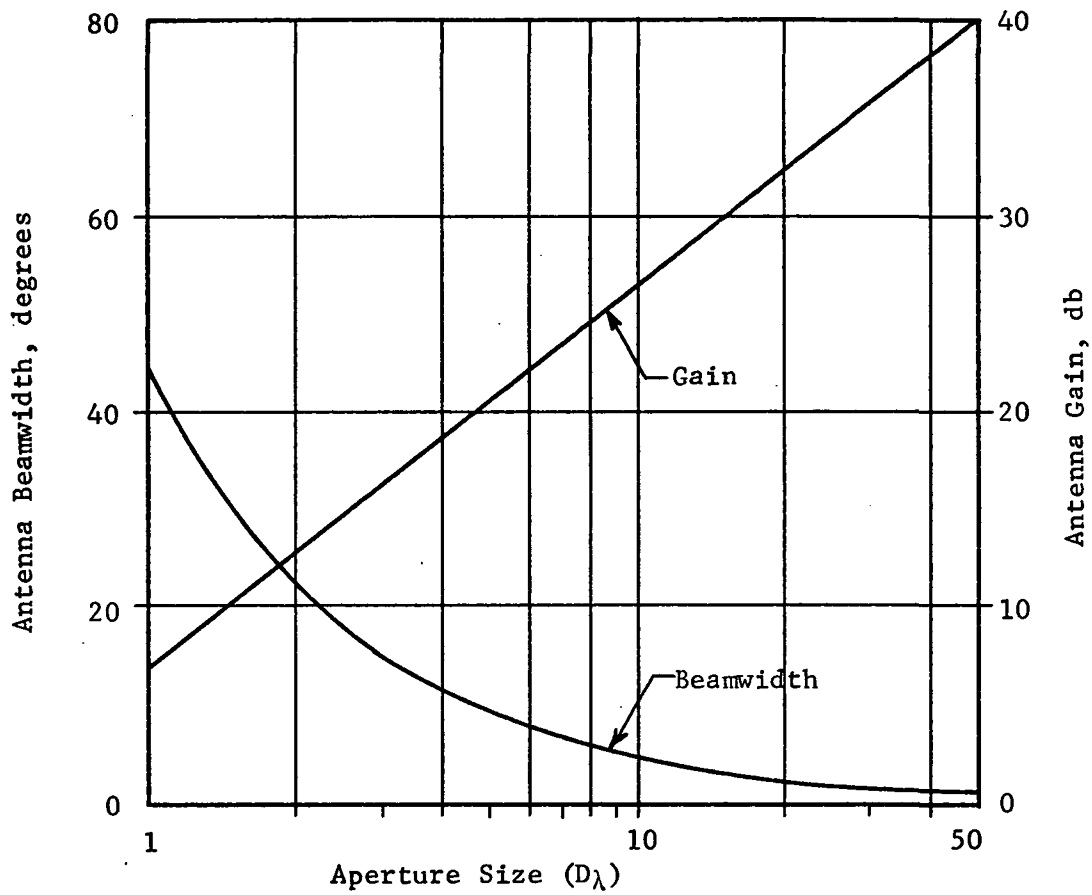


FIGURE 4-11. AVERAGE HALF-POWER BEAMWIDTH AND GAIN FOR AN APERTURE ANTENNA

TABLE 4-2. HARDWARE SPECIFICATIONS AND ESTIMATED COSTS FOR FIVE "STRAWMAN" INTERFEROMETER SYSTEMS

Hardware Specifications and Estimated Costs	Surveillance and Data Collection System (System 1)	Navigation/Surveillance/Data Transfer System: Low Capability (System 2)	Navigation/Surveillance/Data Transfer System: High Capability (System 3)	(Aerial Navigation/Air Traffic Control/Data Transfer) System (System 4)	All-Purpose System (Navigation/Data Transfer/Surveillance (System 5)
User Ground Equipment					
Transmitter Power Output	1 w	10 w	10 w	20 w	1-10 w[a]
Transmitting Antenna Gain	2-4 db	NA	NA	NA	NA
Transmitting/Receiving Antenna Gain	NA	12 db[b]	33 db[c]	3 db	2-35 db[a]
Frequency	1.5 GHz	1.5 GHz	6 GHz	1.5 GHz	1.5 GHz
Transmitter Stability	0.1 ppm	0.1 ppm	0.01 ppm	0.1 ppm	1 part in 10^7 - 10^8
Data Rate	30 bps (up-link)	250 bps (up-link); 100 bps (down-link)	>500 bps (up-link); >500 bps (down-link)	600 bps (up-link); 180 bps (down-link)	30-1000 bps (up-link)[a]; 100-1000 bps (down-link)[a]
Cost	$<1K	$5K-$10K	$25K-$50K	$15-$20K	<$1K-$50K
Spacecraft Equipment (50-m Baseline)					
Receiving Antenna Gain	15 db	15 db	15 db	15 db	15 db
Noise Figure	3.5 db	3 db	6 db	3.5 db	3 db
RF and System Losses	3 db	3 db	4.5 db	3 db	3 db
Integration Time	1-5 sec	1 sec	1 sec	1 sec	5 sec
Transmitter Power Output	NA	500 w	500 w	1 kw	500 w
System Performance					
Bit Error Rate	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}
Positioning Accuracy	1-2 km[d]	125-500 m[d]	25-75 m[d]	250 m	25 m-2 km[a]
Number of Channels	Limited only by frequency allocation	1000	500	150	1000 (low bandwidth, ~100 Hz); 1000 (high bandwidth, ~ 1000 Hz)

(a) Depending on application.

(b) 0.5-m dish.

(c) 1-m dish.

(d) 90°-15° elevation angles.

interferometer system to compete effectively with other types of positioning and/or navigation systems with regard to performance.

4.5.2.1 System 1: Surveillance and Data Collection. For a system capable of providing a surveillance function and limited data-collection capabilities, the user ground-system costs should be relatively low. The user equipment for this system consists of a transmitter only, with the necessary data modulators, interfaces with the data sources, and antenna. The antenna is simple and inexpensive. The transmitter power output requirements are minimal and the data rates are low. A transparent satellite concept with central-site processing is visualized. The user ground equipment costs for such a system should be less than $1000 in reasonable quantities.

The major constraints on the positioning accuracy and data rates with this system are the necessity for a nonsteerable, wide-beamwidth ground antenna. A larger interferometer baseline or more integration time would increase the positioning accuracy but the data rate would remain the same. Only increased transmitter power outputs would improve the data rate. Moving to a higher frequency would also improve the positioning accuracy but would reduce the data rate.

4.5.2.2 System 2: Navigation/Surveillance/Data Transfer (Low Capability). For a low-capability system of this type, a transparent satellite concept with central-site processing would appear to be a satisfactory approach. In this case the user ground equipment would consist of both a transmitter and a receiver along with the data modulator and demodulator, data source interfaces, and an antenna with a beamwidth that would allow manual pointing or a simple mechanical clockwork-type tracking mechanism.

The user ground equipment costs of such a system are estimated to range from $5000 to $10,000 each in reasonable quantities with the major costs associated with the transmitter. The transmitter is visualized as consisting of a 10-w solid-state power amplifier following the reference oscillator, frequency multiplexers, and drive circuits. The receiver can utilize a low-noise FET (Field Effect Transistor) preamplifier and noise figures of 3 db should be easily achievable.

The positioning performance of this system can be improved, if desired, by using a longer integration time. This may, however, reduce the total number of users since the extent to which time multiplexing could be used would be reduced. The data rates are determined by the available power output from both the spacecraft and the ground system and in general could not be increased significantly without going to a much larger ground antenna.

4.5.2.3 System 3: Navigation/Surveillance/Data Transfer (High Capability). A high-capability system with navigation/surveillance/data transfer capability would require the use of an antenna mount capable of tracking the spacecraft. Again, using a transparent satellite configuration with central-site processing, the user ground equipment consists of a transmitter, receiver, modulation and demodulation equipment, data interfaces, and a steerable antenna with acquisition and tracking circuits.

The costs associated with a system of this type are dependent on the antenna size and the tracking requirements. Figure 4-12 illustrates the estimated costs of large parabolic reflector antennas as a function of the antenna size (Cuccia and Hellman, 1975). These costs do not include the cost of a steerable mount and the necessary tracking electronics. The antenna configuration required for this system is similar to that designed for the MARISAT system by Scientific Atlanta Corporation. This is a 1.2-m fully stabilized antenna on a four-axis pedestal that is controlled by gryos which sense the ship roll. It is estimated that, in quantity, similar antenna/pedestal configurations could cost in the range of $25,000 to $50,000.

The positioning accuracy of this system may be improved to some extent by increasing the integration time, however, the random-noise contribution to the system error is sufficiently small that other effects are major contributors. Decreasing this component further by increased integration time may not be of significant benefit.

4.5.2.4 System 4: Air Traffic Control System. For aircraft navigation or air traffic control applications, a system capable of providing a near continuous up-date rate along with a relatively high accuracy is necessary. A transparent satellite concept with central-site processing could be used. The aircraft would carry a transmitter and receiver unit operating on separate frequencies along with a digital MODEM and necessary interface equipment. The

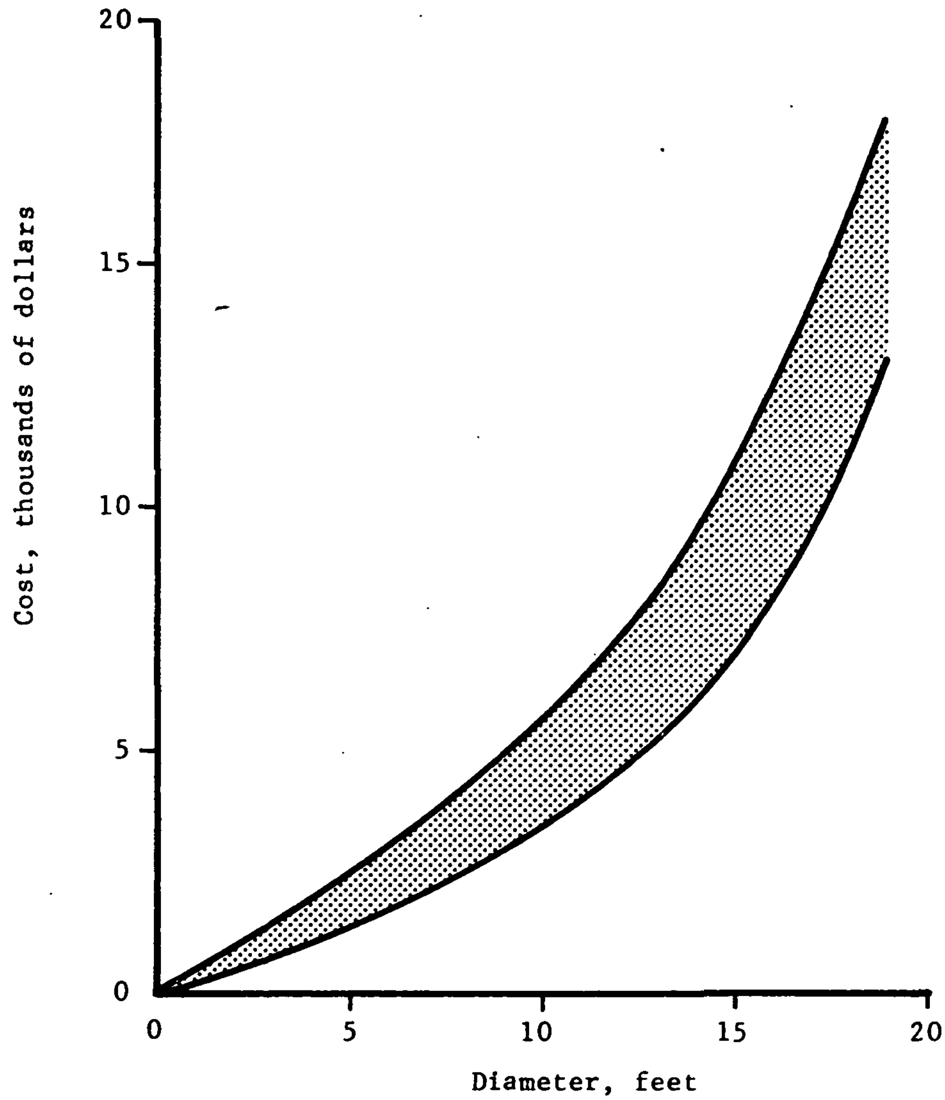


FIGURE 4-12. ANTENNA COST VERSUS DIAMETER

Source: Cuccia & Hellman, 1975

aircraft antenna would need to provide over 160^{o} of vertical coverage and thus would have a low gain.

This application represents the most difficult for an interferometer system. The requirement for high accuracy dictates the need for a large baseline length and high user transmitter power outputs, since the low transmitting antenna gain tends to reduce the effective signal-to-noise ratios at the spacecraft. The essentially continuous up-date rate requires low integration times and imposes a severe burden on the spacecraft-to-user down-link data rate requirements. If the minimum information required by the aircraft is identification, time, and position then it is estimated that data rates of about 180 bps are required. If a maximum power output of about 1 kw is available at the spacecraft then only around 150 separate 180-bit channels are available if bit error rates of 10^{-6} are desired.

The only way to alleviate this constraint would be through the use of a steerable antenna on the aircraft. If a reasonably low cost, phased-array antenna were available for use on the aircraft, a substantial increase in the system performance both in accuracy and the number of users would result. Phased-array technology has been explored and/or used in various military systems and also in spacecraft applications. Such technology should be explored for aircraft and ground applications for the interferometer.

Using a conventional antenna (not a phased array), it is estimated that the cost of the user ground equipment for the above-described system configuration would be of the order of $15,000 to $20,000.

As has been indicated, for all of the above "strawman" configurations various parameter trade-offs are possible. For all but System 3 (high-capability navigation) the accuracy can be increased by increasing the baseline length, the ground transmitter power output, the integration time, or the frequency. The accuracy for System 3 may be limited by factors other than the receiver signal-to-noise-ratio and thus could not necessarily be increased by changes in these hardware parameters.

Increasing the frequency will result in a reduction of the maximum possible data rate, which is of course independent of the baseline length and integration times.

4.5.2.5 System 5: All-Purpose (Navigation/Data Transfer/Surveillance). If air-traffic control applications are not considered, then an interferometer system can be configured which can satisfy surveillance, low-capability and high-capability navigation, and data-transfer applications simultaneously by simply using different ground-hardware configurations. The spacecraft hardware would then be independent of the specific user applications. The frequency most suitable for such a system would be at the low end of the 1 to 8-GHz region and 1.5 GHz has been selected to illustrate typical system parameters.

The performance of such a system depends primarily upon the ground-station ERP and thus the power output and antenna gain. System cost could range from less than $1,000 to $50,000. The major cost differences result from the costs of the transmitter power amplifier and whether a simple broadbeam antenna is used or a narrowbeam steerable antenna with automatic tracking.

5.0 SURVEY OF COMPETITIVE NAVIGATION SYSTEMS AND COMPARISON WITH THE INTERFEROMETRY SYSTEM

5.1 Survey of the Systems

Navigation systems can arbitrarily be grouped under five types: celestial, acoustic, inertial, surface-based radio, and satellite. There are over 100 systems based on variations in the above basic types in use today; all have strong points and limitations and no single system can satisfy all purposes. Various criteria are applied in evaluating the satellite interferometry system against the existing major systems, e.g., accuracy of positioning, update interval, extent of coverage, ability to meet a variety of user applications (e.g., shipping, fisheries, specialized operations, air traffic control, etc.), economy, user advantages, reliability, and maintainability. All of these criteria are important, but accuracy, coverage, update interval, and economy (especially the user aspect) are considered of greatest importance.

The accuracy of positioning, as discussed here, is related to the ability of the system to determine a position as close as possible to its known or true position in space. It should not be confused with the precision of the system which is its ability to repeat the measurements under similar conditions. Coverage relates to the ability of the system to give reliable and satisfactory results under normal operations in a given area (regional or global).

Before proceeding with the comparison of the interferometry system with the other systems, a brief description of the various aspects of these "other" systems including concept, characteristics, capabilities, economy, and user advantages will be presented in the following discussion. It should be emphasized, however, that only the competitive systems will be discussed in relatively more detail while representatives of other systems will be merely mentioned for the sake of completeness. Almost all of the competitive systems are either of the surface-based radio or satellite type.

5.1.1 Radio Navigation Systems

Surface-based radio navigation systems depend on the propagation of radio waves. Of the various radio navigation systems, only the LORAN (A and C) and Omega provide sufficient regional or global coverage on the Earth and can be considered competitive with the interferometry system so far as its application for position determination is concerned. These systems are also known as hyperbolic navigation systems because the lines of position they produce are of hyperbolic form, in contrast with the circles and radial lines associated with systems that measure distances and bearings, respectively. "The hyperbolic method offers a superior combination of accuracy and range to that of any ground-based system employing bearing measurement, while confining the transmission of radio signals to the ground stations and so avoiding the saturation problem implicit in the two-way transmission required for the direct measurement of distance" (Beck, 1971).

The basic procedure to determine position from these systems involves time measurements multiplied by velocity of propagation. Two basic measuring (time) techniques are available:

(1) Direct - the time interval between the receptions of the radio pulses from two different stations is directly measured.

(2) Phase-comparison - the time difference is derived by measuring the phase difference between the pulses received.

In both techniques, the accuracy of measurements is highly dependent on the velocity of propagation of radio waves, the atmospheric conditions, land and water along the propagation path, timing, geometry of the transmitters with respect to the receivers and several other factors. Generally, the higher the frequency used, the greater the accuracy of the measurements and the shorter the range. Lowering the frequency increases the range but decreases the accuracy.

Another important factor which affects the performance of these systems is the type of signals transmitted from the ground stations. A train of synchronized single pulses is the basis for several hyperbolic systems;

alternatively, synchronized continuous wave (CW) signals can be employed. As well as being free from the phase ambiguity, the single-pulse method permits discrimination against signals arriving by skywave mode of propagation but requires a relatively high carrier frequency and a wide bandwidth. The CW method permits a greater accuracy of time difference and a wide choice of carrier frequency, but with the penalty of cycle ambiguities.

The fundamental difference between LORAN A, LORAN C, and Omega lies in the differences in some or all of the following:

(1) Frequency

(2) Type of signals (pulse or CW)

(3) Method of time measurement.

Their specific differences can be readily seen from Table 5-1. The consequent system capabilities are presented in Table 5-2. The differential mode of Omega is a technique to obtain increased accuracy over a relatively small area where the error in the Omega readings at a monitoring station of known location is broadcast so that the users can make the necessary corrections. Maximum range for this mode is about 400 km.

These systems have been applied primarily for marine navigation which is essentially determining position in two dimensions (latitude and longitude). "Considering the trends so far revealed by the applications and studies of Omega as an airborne navigation aid, the principal conclusion is that the initial hopes that Omega could be a single system may have to be dropped. However, Omega as part of a hybrid navigation system with simple air data or Doppler dead- reckoning would seem likely to be able to provide valuable service at a cost well below that of the Inertial Navigation installations used in the Boeing 747 Jumbo Jet and to be able to be cost effective to the operation of the large proportion of commercial aircraft" (Beck, 1971).

Further extensions of the Omega system, for instance, Omega Position Location Equipment (OPLE) using geostationary satellites for position determination and data collection are discussed in subsection 5.1.2.2 "Other Satellite Systems/Experiments".

TABLE 5-1. FUNDAMENTAL DIFFERENCES BETWEEN LORAN A, LORAN C, AND OMEGA SYSTEMS

System	Frequency	Type of Signal	Method of Time Measurement
LORAN A	1750-1950 kHz	Pulse	Direct
LORAN C	90-110 kHz	Pulse	Both direct (coarse) and phase difference (Vernier)
Omega	10-14 kHz	CW	Phase difference

TABLE 5-2. SYSTEM CAPABILITIES OF LORAN A, LORAN C, AND OMEGA

System Characteristics	Capabilities of System Indicated[a]		
	LORAN A	LORAN C	Omega
Baseline length (km)	200-400	900-1300	9000-11000
Range from center of 4-station chain (km)	1500 (GW) 2600 (SW)	2200 (GW) 5500 (SW)	400 (DM) 6500 (CM)
Accuracy (km)	1-4 (GW) 9-13 (SW)	0.1-1.0 (GW) 6-9 (SW)	2-4 (CM) 0.2-1.0 (DM)
Present (Earth) coverage (%)	15	4	Global
No. of stations required for global coverage	550	90	8
Cost of operation ($\$/km^2$)	3	3	0.3
User cost ($)	1000-4000	3000-5000	3000-5000

(a) GW - Ground wave
SW - Skywave
CM - Conventional mode
DM - Differential mode.

5.1.2 Satellite Systems

One of the immediate results of the observations made to the first earth satellite (Sputnik) was the development of the TRANSIT, the Navy Navigation Satellite System (NNSS) which has been in continuous operation since January of 1964. Even though considerable navigation satellite development analyses have been performed, NNSS remains the only navigation satellite system operational today and perhaps will be for some time to come. The analyses have been conducted not only to determine the optimum approach for improving the present NNSS, but to investigate the practicality of satellite systems for communication, precise time transfer, surveillance, air-traffic control, etc. These analyses involving various satellite systems and configurations have been carried out by the Department of Defense (DOD), NASA, the Department of Commerce (DOC), and the Department of Transportation (DOT)/Federal Aviation Administration (FAA).

The DOD activities have been concerned basically with the three dimensional position and velocity and precise time transfer (Parkinson, 1974), while the other organizations are studying systems whose capabilities include combinations of position, velocity, time transfer, surveillance, and traffic control. In addition, the DOD is responsible for the operation of the NNSS. It is, therefore, considered appropriate to begin the description of the satellite systems with a discussion of the DOD activities followed by a brief survey of the other systems. Since other applications like search/rescue and collision avoidance, are implied in the above basic capabilities, these additional applications may not be explicitly referred to in the following discussion.

5.1.2.1 DOD Activities in Satellite Navigation. These activities, which began with the development of the TRANSIT Navigation System (officially in December, 1958), resulted in an operational worldwide navigation aid since 1964. However, for a variety of reasons which will be discussed later, this system does not satisfy a broad base of users, particularly those users who are concerned with dynamics in their positioning or navigation problem. Consequently, attempts have been made to move ahead to a global positioning system that has the potential for replacing TRANSIT and serving host of other users as well. TIMATION system of the U.S. Navy and System 621B of the U.S. Air Force represent two of these attempts. A combination of the concepts of these two systems resulted in the evolution of the Global Positioning System (GPS) now renamed the NAVSTAR Global Positioning System. Consequently, the TRANSIT and the NAVSTAR will be considered in this discussion.

<u>TRANSIT (NNSS) System</u>. Currently, this system consists of five fully operational satellites having the following common and fundamental characteristics (Black, et al., 1975):

(1) Circular, polar orbit, approximately 1100-km altitude.

(2) Highly precise frequency standard which drives two transmitters at (nominally) 150 and 400 MHz.

(3) Satellites broadcast their orbital parameters from an on-board memory system which is updated every 12 hours by transmissions from a ground injection station; time marks are also transmitted.

(4) Orbits of these satellites are determined through Doppler tracking of the satellites, four stations forming the operational tracking system.

(5) The user is able to compute a position fix based on data collected during a single satellite pass. These data consist of:

   (a) The measured Doppler frequency shift

   (b) The two-frequency ionospheric refraction correction

   (c) Satellite orbit parameters

   (d) Accurate time marks.

These are the basic elements of the system. Many of the details have been omitted for the sake of brevity. The reader is referred to Black, et al., (1975, p 9) and the numerous references given by him.

The accuracy of the system for navigation purposes depends on a number of factors, the most important of which is the motion of the user. For a fixed user, a position accuracy of about about 40 to 50 m has been reported by Black. Similar results were reported for a ship at dockside (Stansell, 1971). But, any error in the estimation of the speed of the user will result in a corresponding error in the position at the rate of about 800 m for meter-per-second speed error (Black, et al., 1975).

Since the orbits of all the satellites of this system are polar with their nodal longitudes more or less equally distributed around the equatorial plane, the navigational coverage of this system is global. However, a positional fix for a user is available only once every 1-1/2 hours at moderate latitudes since the total number of satellites in the system is small. The waiting period is latitude dependent being longer near the equator and shorter in high latitudes.

Because of the failure of the TRANSIT system to meet most of the essential and desirable characteristics of a satellite navigation system (such as those in Table 5-3), the U. S. Navy has been considering several approaches (Table 5-4) for upgrading its navigational capabilities. However, so far as is known, no schedule has been developed for this upgrading. For the same reason, the DOD has approved a multi-Service program (NAVSTAR Global Positioning System) in an attempt to develop the characteristics in Table 5-3. This system is discussed next.

<u>NAVSTAR Global Position System</u>. NAVSTAR represents a combination of the concepts of two candidate systems developed for the Defense Navigation Satellite System (DNSS): TIMATION by the U. S. Navy and System 621B by the U. S. Air Force. The characteristics envisioned for the TIMATION system are:

(1) The 27 satellites in circular orbits would be in three planes of 9 satellites each at approximately 14,000-km altitude; the orbital periods would be approximately 8 hours, orbit inclination would be 55° or higher; the three planes would be equally spaced in their ascending nodes.

(2) The four ground stations located on U. S. territory would provide the necessary tracking, time management, and system control.

TABLE 5-3. NAVIGATION SATELLITE SYSTEM CHARACTERISTICS[a]

Essential Characteristics
1. Worldwide coverage
2. High accuracy
3. Common grid capability
4. Continuous availability in real time
5. Passive user/nonsaturatable system
6. Operation with dynamic users
7. Acceptable survivability, security, anti-jam
8. Satisfactory portability/size/weight
9. Minimal frequency-allocation problems
10. Freedom from ambiguities
Desirable Characteristics
1. All ground stations on U. S. territory
2. Minimum propagation limitations
3. Acceptable operation under water
4. Provide worldwide time reference
5. Compatibility and integrability with other military/civil systems
6. Evolutionary growth from research and development to operational capability

(a) Source: Decker (1974).

TABLE 5-4. APPROACHES CONSIDERED FOR IMPROVEMENT OF TRANSIT[(a)]

Concept
Satellite Constellation Expansion
- Reduces time between positional fixes
Inclusion of Ranging Signal - PRN/BINOR[(b)]
- Allows ranging - Shortens positional fix interval - Improves accuracy - Improves operation in dynamic environment - Enhances anti-jamming acquisition performance
Improved Fix Program in Receiver
- Provides greater flexibility - Allows use of simple receiver - Use of shorter Doppler counts - Decrease of required transmission duration
DISCOS[(c)] Ephemeris Accuracy Improvement
- Improves accuracy of positional fixes - Allows longer time between satellite memory updates

(a) Source: McDonald (1974).

(b) PRN/BINOR = Pseudo-Random Noise/BINOR.

(c) DISCOS = Disturbance Compensating System.

The configuration proposed for an operational System 621B consists of 20 geosynchronous satellites at an altitude of approximately 35,000 km, and with an orbital period of 24 hours. Sixteen of the satellites are arranged on four planes inclined 60° to the equator. Their orbits are moderately eccentric (eccentricity = 0.25) and the perigees are located at the northernmost and southernmost points on the orbits. The remaining four satellites occupy an equatorial plane and are nearly stationary in geosynchronous orbits.

These 20 satellites form four constellations of five satellites each, and each constellation is typically serviced by one master ground station and two signal monitor stations. In both the TIMATION System and System 621B, the user "measures" the ranges between his position and the satellites using the dual-frequency Pseudo-Random Noise (PRN) technique. This means he needs simultaneous ranges to three satellites if he has an accurate and synchronized clock or as many as four satellites if he does not have one.

In comparison to these systems, the operational system of NAVSTAR would deploy three planes of satellites in circular, 18,500-km orbits with an inclination of 63°. Each plane would contain eight satellites. This deployment insures that at least six (and on the average of eight to nine) satellites are continuously in view from any point on the earth. The master control station would be located in the U. S. with four monitor stations located in U. S. territory.

The basic system technique is the same as the one employed in the TIMATION System and in System 621B. The ranges and the range rates are obtained using the dual-frequency PRN navigational signal. The satellite ephemerides and their rates are decoded from the signals received from the satellites. The data from three satellites will give three-dimensional position and velocity of the user and time coordinate if he has an accurate synchronized clock. Without the clock, four satellites will be required.

The activities of this program have been planned in three phases (Parkinson, 1974): Phase I - concept validation (1974-1976), Phase II - system validation (1976-1981), and Phase III - full system production (1981-1986). There is a good possibility that these dates may be advanched by as much as 2 years (AW&ST, 1976). The method of achieving the objectives of these phases will also evolve into the operational system. Parkinson (op. cit.) gives further details of the activities in these phases.

Since the system is still in the experimental phase, nothing definite can be stated concerning its capabilities; however, it is anticipated that it will have the following characteristics and capabilities:

(1) Accurate three-dimensional position and velocity (<10 m and better than 2-3 cm/sec)

(2) Worldwide common grid

(3) Passive and all-weather operation

(4) Real-time continuous

(5) Unsaturable

(6) Low life-cycle cost (system as well as user).

This system is expected to satisfy a variety of user requirements which are divided into seven classes (Table 5-5). Each of these classes require a different type of receiver equipment depending on its requirements.

TABLE 5-5. NAVSTAR-GPS USER CLASS[(a)]

Class	Cost of User Equipment ($1000)	Applications
A	28.0-29.5	Military aircraft (high speed)
B	17.6-25.6	Small aircraft and helicopters
C	13.2-16.3	Commercial aircraft and ships
D	16.3-22.1	Surface vehicles (slow)
E	16.3-18.2	(Man-pack) satellite self-navigation
F	16.3-25.6	Submarines
M	Not available	Missiles

(a) Sources: Parkinson (1974) and AW&ST (1976).

Class A is for the dynamic user in a potentially high jamming environment that demands the ultimate in precision; Class B is for the high dynamic user; Class C is for users who are interested in low acquisition cost with low life cycle cost as well; Class D is for surface vehicles; Class E is a man-pack which also has applications for self-navigation of satellites; Class F is for submarines (Parkinson, 1974); and Class M is for missiles (AW&ST, 1976).

Detailed information on the cost of production and maintenance of the system was not available at this time.

5.1.2.2 Other Satellite Systems/Experiments. The navigation systems described thus far are concerned with position or position and velocity determination only. However, some of the civilian organizations such as NASA and FAA are convinced that navigation alone is not sufficient and that surveillance and traffic-control functions must be included in a worldwide satellite navigation system. Conceptually, a civilian system would employ a two-way link between a ground station and the navigator through two or more satellites. The ground station would frequently advise the navigator of his current position and of local traffic conditions. The collision-avoidance function and weather routing of ships obviously could be handled by such a system approach. Several such systems are being studied and planned.

NASA/GSFC has been involved in several satellite experiments related to navigation, surveillance, and traffic control. These experiments include the Omega Position Location Equipment (OPLE), Global Rescue Alarm Net (GRAN), Interrogation, Recording and Location System (IRLS), and Position Location and Aircraft Communication Experiment (PLACE). In addition to these experiments, the Maritime Administration (MARAD) of the DOC is involved in the Maritime Satellite (MARSAT) system studies and the FAA of the DOT is experimenting with the Aeronautic Satellite (AEROSAT) system. Due to the overlapping nature of the experimental objectives of PLACE, MARSAT, and AEROSAT, these experiments are carried out under an integrated test plan by the sponsoring agencies concerned (NASA/GSFC, et al., 1973). Among the NASA experiments, only the PLACE program is still active. However, the other experiments are also briefly described here since they have demonstrated certain capabilities related to the navigation, surveillance, and traffic-control functions.

The systems and experiments mentioned above are all sponsored by U. S. agencies with the exception of AEROSAT which is a joint program by DOT/FAA, ESRO, and Canadian Ministry of Transportation, Department of Communication. This list is not complete without mentioning Project GEOLE (Brachet and Lefebvre, 1975) sponsored solely by the French National Center for Spatial Studies (CNES). This satellite is similar to the NNSS in configuration using a reversed measuring technique with less system capabilities. It is not considered to be a viable navigation aid competitive with the other U. S. systems considered for the future. Consequently, this system will not be described here.

OPLE. The OPLE experiment (CSC, 1971) was conceived and conducted by NASA/GSFC in 1967. Its objective was to demonstrate the feasibility of using the VLF Omega navigation system in conjunction with geostationary satellites for a position-determination and data-collection system. Three satellites are required to provide global coverage (with the exception of the polar areas).

The OPLE system experiment consisted of one geostationary satellite (ATS-3) VLF/VHF user equipment platform, a control center for satellite command and acquisition, and the Omega navigation system. The user/platform employs a transponder which receives the VLF omega signal, converts it to a VHF frequency signal, and transmits it to the satellite. The control center receives the signal from the satellite and determines the geographic position of the user and then retransmits the position information to the user via the satellite.

Also, the control center receives the VLF Omega signal to derive timing and determines the status of the Omega network and which of the platforms are to be interrogated. The system can be used to collect data from remote stations (buoys, balloons, etc.) and for search and rescue (SAR) operations. However, there are some limitations in the SAR operations since the system depends on the Omega system that has inherent ambiguity resolution problems. The Omega ambiguity in ship location is usually resolved through maintenance of lane count. To avoid this ambiguity the Navy has experimented with using a fourth Omega frequency which will be described under the GRAN experiment using the Lincoln Experimental Satellite-6 (LES-6). The OPLE experiment has demonstrated that the Omega signal can be relayed through the satellite with an estimated accuracy of 2 to 4 km. The time required for a position fix is about 3 minutes. The system could accommodate several thousand users. The transponder cost is estimated about $1,000 and the cost of the control center is a few million dollars. Satellite costs depend on the type of satellite selected. The 1968 experiment results on-board ship gave accuracies of 2-7 km (1 to 4 nmi) in comparison with ship navigation fixes.

GRAN. The GRAN experiment (Morakis, et al., 1971) was an expansion of the OPLE. This experiment was conducted by the Naval Air Test Center (in cooperation with NASA) in the Fall of 1974 using the LES-6. The experiment was designed to provide a worldwide search and rescue (SAR) capability using Omega navigation and geostationary satellites and to provide real-time distress alerting, identification, and position location (Calise and Crawford, 1974). GRAN comprises portable battery-powered search and rescue communications (SARCOM), appropriate frequency translators aboard a geostationary satellite, and a network of three or more ground receiving stations in different parts of the world. A fourth frequency (10.880 kHz) was added to two Omega transmitters to allow better identification of the lane ambiguity from 133 km (72 nmi) (as it is in the regular three-frequency Omega) to 667 km (360 nmi).

The location of the SARCOM in distress is accomplished in three steps:

(1) Reception of signal from one satellite to determine from which one-third of the earth it originates

(2) Coarse lane identification by either:

   (a) Signal-to-signal comparison of the relayed Omega. This reduces the area to about 2000 to 4000 km (1000 to 2000 nmi), or

   (b) Difference in time of arrival of the Omega pulse envelope to determine a 667-km (360-nmi) lane

(3) A maximum estimator to refine this estimate to 2 to 4 km (1 to 2 nmi).

IRLS. IRLS is an experimental system developed at NASA/GSFC and placed in orbit on the Nimbus-3 satellite. Its purpose is to demonstrate the location and tracking of remote unmanned platforms. The spacecraft interrogates the platform equipment, identifies it, and locates it. Two successive interrogations are made from different points in the satellite orbit to enable the platform location by triangulation to about 8-10 km. IRLS is essentially a meteorological data-collection system and, although some of the details of the system design may be of interest to navigation, surveillance, and traffic control, the system, as it stands, is totally unsuited to these requirements.

PLACE. This is a NASA-funded experiment as an extension of OPLE to obtain engineering data and practical experience for determining the operational feasibility of an Air Traffic Control (ATC) satellite system operating in the aeronautical L-band. The principal experiment system elements, as originally conceived (STK, 1970), of the PLACE system consist of the parabolic antenna and communication transponder of the NASA ATS-6 satellite, appropriate aircraft transmitters and receivers, and a primary control center which is equipped with a VLF transmitter (e.g., an Omega station).

The PLACE experiment has two main objectives: (1) to demonstrate the feasibility of two-way communication between ground terminals and aircraft, and (2) to investigate the feasibility and evaluate the absolute and relative accuracies of several position-location techniques using a single satellite. These techniques relay various signals from the aircraft through the satellite to the control center for data processing and position determination.

These objectives are to be achieved by conducting three types of experiments: ground-based engineering, ground-based simulation, and inflight performance. Since the inflight performance experiments objectives are very similar to those of other systems (MARSAT and AEROSAT to be discussed later) which calls for the same satellite system configuration, these experiments are conducted on an integrated basis in close cooperation with FAA/ESRO/CANADA (AEROSAT) and MARAD (MARSAT) using the ATS satellites. These integrated tests will address the concepts and technology applicable to aeronautical satellite communication and ATC systems and to maritime satellite communication and surveillance/navigation systems. They will be conducted utilizing the NASA PLACE equipment as the test bed and therefore will satisfy the original purpose of NASA's PLACE.

Thus far, PLACE has been able to demonstrate (Gallicinao, 1975) the feasibility of: (1) L-band voice test with aircraft and with ship communications and ground stations, and (2) limited air-traffic control (aircraft and simulated input). The position location accuracy with the mobile stations has not yet been demonstrated. It appears that a 10-m precision in the range measurement is necessary to achieve better than 2-km position accuracy.

Cost information on the system is not available at this time.

MARSAT.* This conceptual system, consisting of shore-based and ship terminal subsystems, is expected to provide, in conjunction with two geosynchronous equatorial satellites, "excellent communication and surveillance coverage, allowing the maritime community to link up with a Marine Data Coordination Center (MDCC) and other distributed support and control facilities" (McDonald, 1974). The ultimate objective of this system is to improve ship productivity, safety, and control. This concept has been verified by independent experiments conducted by some user groups, e.g., Exxon Corporation in cooperation with the General Electric Company where voice, teletype, facsimile, and slow-scan TV communications and position-fixing capabilities were successfully demonstrated (LaRosa, et al., 1974). The current efforts are addressing the technical feasibility of the approach by utilizing and adapting existing state-of-the-art hardware and systems to the shipboard, shoreside, and space applications.

In the basic configuration considered, one of the two geostationary satellites will be used as the primary satellite to accommodate the full-duplex communication for the voice, ranging, and other data transmission. This satellite will transpond the ship-to-shore and shore-to-ship communication/ranging signals through two independent C to L and L to C transponders operating in the noncoherent frequency translation mode.

The second satellite will be to serve the function of relaying the ranging signals transmitted from another ground station to generate a second line of position as required to complete the position-determination function.

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*Private communications with personnel at MARAD indicated that as of February 13, 1976, there is no program called MARSAT. MARAD has only a proposal(s) related to such a concept, but nothing definite to report.

The shipboard satellite terminal communication equipment consists of an L-band transmitter, receiver, and antenna subsystem capable of supporting full-duplex voice, data, transmission, and ranging communications (MARAD, 1974).

The experiments related to this concept are being conducted using the ATS satellites in close cooperation with NASA/GSFC, sponsors of the PLACE, and with DOT/FAA, ESRO, and CANADA, cosponsors of the AEROSAT program. It is not certain, at this time, that this concept will evolve into an approved program. Even if it did, its implementation on a global basis involving a variety of other agencies' activities and national interests is, perhaps, several years away.

AEROSAT. This is a joint U. S./Canadian/European satellite program. The configuration of the satellite system is basically similar to the one used in the MARSAT concept. The space segment of this system consists of a minimum of two geostationary satellites which perform the relay of the communications between ground and aircraft and between pairs of ground stations. They also enable independent surveillance by range measurements. The ground segment consists of ground facilities including an earth terminal, a control center, interface with user stations, and test systems.

Each of the primary participants (U. S., Canada, Europe) will provide one or two ground facilities. The airborne segment provides for the L-band avionics of the system for communication and surveillance reception and transmission, interface with aircraft voice, data input/output equipment and specified aircraft instrumentation.

The program approved by all the primary participants is a scaled-down two-satellite system to provide aircraft communication and position fixing over the North Atlantic. This program will provide an aeronautical satellite capability to (AW&ST, 1974):

(1) "Provide experience in technical, operational, economic, and management areas prior to establishing a fully operational capability.

(2) Evaluate the technical and operational performance of voice and data communications between ground and aircraft flying within the coverage area.

(3) Permit extensive evaluation of dependent and independent surveillance parameters.

(4) Permit wideband experimentation."

The first of the AEROSAT spacecraft planned for the program is expected to be launched in late 1977 or early 1978. It may also be interesting to note that an informal agreement between FAA, Air Travelers Association, and Congress includes a provision that an operational AEROSAT will not be developed until it is actually needed (ibid). This indicates that the evolution of this program into a fully operational system will not be realized in the near future.

5.2 Comparison of the Systems

Since the feasibility of interferometry systems for navigation or positioning has yet to be demonstrated, a precise definition of the characteristics and capabilities of such a system is not possible. Moreover, most of the navigation systems with which they would be competitive are either in the planning or experimental stages, and their various subsystems are not fully defined. Consequently, a comparative evaluation of these systems, in a strict sense, is not proper nor would it be meaningful. However, a comparison of these systems with respect to their theoretical, or rather, prospective characteristics and capabilities as found in this study is considered reasonable, and such a comparison is presented here to indicate the potential and viability of interferometry systems for various applications.

5.2.1 Relative Performance of the (Navigation) Systems in Specific Areas

The performance and cost of the various systems in specific areas will be discussed here so that an overall evaluation of their relative performances can, subsequently, be made.

5.2.1.1 Coverage. All of the systems listed in Table 5-6 with the exception of LORAN-C can be made to provide global coverage. The Omega system, for example, with eight transmitters can provide such coverage. The OPLE, PLACE,

TABLE 5-6. MAJOR CHARACTERISTICS OF INTERFEROMETRY AND OTHER COMPETITIVE SYSTEMS

System	Frequency	Type of Position Fix	Range/Coverage	Position Accuracy	Position Update Interval	No. of Sat. for Position	Min. No. of Ground Stas. for Position	No. of Users/ Channels	Applications	User Equipment Characteristics	User Equipment Cost ($)
LORAN C	90-110 kHz	Hyperbolic	2800-5500 km	100 m-1 km	Continuous	--	3	Unlimited	N(2D)	Passive	3-5K
Omega	10-14 kHz	Hyperbolic	Global	4-9 km (abs.) 200 m (relative)	Continuous	--	3	Unlimited	N(2D)	Passive	3-5K (1 frequency -marine) 25-35K (airborne)
OPLE	--	Hyperbolic	Global -70° < Lat <+ 70°	4-9 km	Continuous	1	3 (+1 Control)	40?	S/DC	Active transponders	<1K
NNSS (TRANSIT)	150,400 MHz	Doppler	Global	350 m	90 minutes	1	None	Unlimited	N(2D)	Passive	40-100K
NAVSTAR/GPS	1200, 1600 MHz	Ranging (PRN)	Global	10 m	Continuous	4	None	Unlimited	N(3D) V(3D)	Passive	13-30K
PLACE	Not available	Ranging (tone)	Global -70° < Lat <+ 70°	~2 km	Continuous	2	2	200	N(2D) TC/DT	Active transponder	Not available
MARSAT	1660 MHz	Ranging (tone)	Global -70° < Lat <+ 70°	~2 km	Continuous	2	2	~1000	N(2D) S TC/DT	Active transponder	Not available
AEROSAT	1543.5-1578.5 MHz 1622.5-1660.0 MHz	Ranging (tone)	Global -70° < Lat <+ 70°	~4 km	Continuous	2	2	~1000	N(2D) S ATC/DT	Active transponder	Not available
Interferometry System 1	1500 MHz	Angles (interferometry)	Global -70° < Lat <+ 70°	1-2 km	Continuous	1	2	Unlimited*	S/DC (surface)	Active transmitter	<1K
2	1500 MHz	Angles (interferometry)	Global -70° < Lat <+ 70°	125-500 m	Continuous+	1	2	1000+	N(2D)/DT S(surface)	Active transponder	5-10K
3	6000 MHz	Angles (interferometry)	Global -70° < Lat <+ 70°	25-75 m	Continuous+	1	2	500+	N(2D)/DT S(surface)	Active transponder	25-50K
4	1500 MHz	Angles (interferometry)	Global -70° < Lat <+ 70°	250 m	Continuous+	1	2	150+	N(2D)/DT S(air)	Active transponder	15-20K
5	1500 MHz	Angles (interferometry)	Global -70° < Lat <+ 70°	25 m-2 km‡	Continuous+	1	2	1000+	N(2D)/DT S(surface)	Active transponder	1-50K‡

*Subject to total frequency allocation.

+The number of users depends on the update interval. See Table 7-2.

‡Depends on the user equipment.

N - Navigation
S - Surveillance
DC - Data Collection
DT - Data Transfer
ATC - Air Traffic Control
TC - Traffic Control
2D - Two-Dimension
3D - Three-Dimension
V - Velocity

MARSAT, AEROSAT, and the various interferometry systems with one or two satellites, as the case may be, give only regional coverage to the extent that the satellites are within radio visibility. However, this coverage can be extended to global (with the exception of the polar regions) with the deployment of additional satellite systems.

5.2.1.2 Accuracy of Positioning. Among the surface-based radio systems considered here, LORAN-C gives the highest accuracy in position (100 to 1000 m), but it lacks the range to cover the vast oceanic areas. Similar range of accuracy is available from the TRANSIT system. The accuracy expected of the NAVSTAR/GPS is still better. The GPS has an important and advantageous feature: The availability of user equipment at varying levels of sophistication/cost permits him to meet both his budget and application requirements. PLACE, MARSAT, and AEROSAT, even though their primary objective is communication and traffic control, have reasonable accuracy (2 to 4 km).

As has been indicated earlier in the report, the accuracy of the interferometry system depends mainly on the length of the baseline and on the random component of the phase-difference measurement which, in turn, depends on several factors including the integration time. With an accuracy of about $0^\circ.1$ ($1\ \sigma$) in the phase difference measurement, a position accuracy of 50 m is possible with a 1-second integration time for a 50-m baseline. If it is feasible to have longer baseline, greater accuracy is possible with increased integration time and larger antennas. Thus, the accuracy of the interferometry system is nearly comparable to that expected of the GPS.

5.2.1.3 Position Update Interval. All of the systems considered here with the exception of TRANSIT, have almost continuous positioning capability so long as the user is within the range of the system. This is true, without any limitation, with the systems requiring passive user equipment. However, in the case of systems which can accommodate only a limited number of users at a given time (OPLE, PLACE, MARSAT, AEROSAT, and interferometry), it is possible to increase this number by providing time slots for each user. The update interval, in this case, is the difference between consecutive time slots.

5.2.1.4 Capabilities. LORAN-C, Omega, and the TRANSIT systems provide only a two-dimensional position capability. The NAVSTAR/GPS is expected to provide three-dimensional position and velocity. These systems are also used for precise time transfer. The OPLE system was designed to provide only surveillance and data-collection capabilities. PLACE, MARSAT, and AEROSAT systems are capable of not only two-dimensional navigation and surveillance but also of traffic control. The applications of communication, search and rescue, collision avoidance, and data transfer (two way) are implied in the general navigation, surveillance, and traffic-control capabilities.

The candidate or "strawman" interferometry systems considered in this study, have the following capabilities: System 1 is capable of only surveillance and data collection using the simplest possible user equipment; System 2 is for low-accuracy navigation (two dimension), surveillance and data transfer for surface-based operations; System 3 is similar to System 2, but is capable of providing greater position accuracy; System 4 is similar to System 2 except that it can serve airborne operations; and System 5 is an all-purpose system for surface-based operations where the user equipment for Systems 1, 2, and 3 can be used simultaneously with this system.

In principle, Systems 2 through 5 can be used for traffic-control, but the resulting rather drastic reduction in the number of users makes this application economically infeasible. If phased-array antenna equipment is developed for aircraft use, air-traffic control could be accommodated without much loss in capacity for the number of users.

5.2.1.5 Number of Users. Since most of the systems having communication capability are still in the planning or experimental stage, the number of users that could be accommodated in each system has neither been strictly defined nor available. However, from the theoretical point of view, some useful comparison can be made between these systems.

The systems requiring passive user instruments (e.g., LORAN-C, Omega, TRANSIT, and GPS) are unsaturable, i.e., they can have an unlimited number of users at any given time. The other systems have limitations depending on the designed capability of the system. However, as indicated earlier, this capability can be effectively increased by grouping the users according to their update-interval requirements and providing time slots to permit sharing the same channel. For example, the interferometry Systems 2, 3, and 5 can accommodate more than 100,000 users if their required update interval is about 30 minutes, but only about 500 to 1000 users can be accommodated if almost continuous up-date is required.

The systems intended for voice communication and airborne applications will have very limited capacity with respect to the number of users.

The inverse interferometry system (described in Section 4.2.2), which requires only passive user hardware, can serve an unlimited number of users, and the user equipment would appear to be less expensive. However, it should be noted that this unlimited capacity and greater user economy is achieved at the expense of other capabilities (surveillance, data transfer, etc.). In addition, it requires another satellite similarly equipped.

5.2.1.6 User Economy. The user equipment costs, as given in Table 5-6, are only rough approximations, and if the equipment was produced on a commercial scale they should be significantly less. It appears that the equipment for the OPLE system and interferometry System 1 is least expensive. The reason being that these two systems have the most basic and simplest capability (surveillance and data collection) and the complex data processing equipment is located at the control center. The most expensive is for the TRANSIT system and Interferometry System 3. The processing equipment is with the user in the case of the TRANSIT system.

The cost of the simplest user equipment (single frequency) for a surface-based radio navigation system is about $1000 to $5000. The cost of three-frequency receiver equipment (airborne) may be as much as $35K. The cost given for the NAVSTAR system is the design goal cost, not the actual cost.

The costs for MARSAT and AEROSAT are not available; but it is estimated, considering the configuration of the user subsystem, that they would be in the neighborhood of $20,000. The costs of equipment for Interferometry Systems 2 and 3 are about $5,000-$10,000 and $25,000-$50,000, respectively. The greater cost of System 3 is due to the requirement for a large steerable antenna. Interferometer System 4 equipment cost is estimated at about $15,000 to $20,000. Costs for Interferometry System 5 (combination of Systems 1, 2, and 3) could range from $1,000 to $50,000 depending upon user requirements.

5.2.2 Overall Relative System Performance

An attempt to evaluate the overall relative performance has been made in Table 5-7 where the relative performance of each system is rated on a descending scale of 5 through 1. Seven system characteristics capabilities are evaluated (coverage, position accuracy, position update, applications (surveillance, navigation, data transfer), number of users, and user equipment cost. The standing of each of these systems with regard to overall performance is given in the last column of this table by totaling up the points given for individual characteristics.

This method of evaluation of the overall performance is, of course, only arbitrary, and is designed to give some idea of the relative performance of each of the systems under consideration. The evaluation indicated that the interferometry systems rank the highest considering all capabilities. The GPS ranks first followed by the surface-based radio navigation systems and TRANSIT in that order among the existing or planned systems which provide navigation capability only (two or three dimensional). These have neither surveillance nor traffic control capabilities. Among the two systems which are capable of surveillance only, the Interferometry System 1 ranks better than OPLE.

All of the remainder of the systems are capable of navigation, surveillance, and two-way data transfer. Among these AEROSAT and MARSAT are expected to have voice communication also. All of the interferometry systems which have two-way communications, rank higher than the AEROSAT and MARSAT systems, and Interferometry System 5 is outstanding. This system has the following options depending on the type of user equipment:

(1) Surveillance and data collection

(2) Low-accuracy navigation, surveillance, and data transfer

(3) High-accuracy navigation, surveillance, and data transfer.

With the use of phased-array antenna equipment this system can also be used for traffic-control purposes.

Besides the highest relative performance already indicated, the interferometry systems need only one geostationary satellite to cover an area of the Atlantic Ocean and most of the continent of America.

TABLE 5-7. RELATIVE PERFORMANCE OF THE VARIOUS SYSTEMS

System	Coverage	Position Accuracy	Update Interval	Applications Surveillance	Applications Navigation	TC/DT	No. of Users	User Equip. Cost	Total
LORAN C	3	4	5	--	4	--	5	4	25
Omega	5	2	5	--	4	--	5	4	25
OPLE	3	2	5	5	--	--	2	5	22
TRANSIT	5	4	2	--	4	--	5	1	21
NAVSTAR/GPS	5	5	5	--	5	--	5	2	27
PLACE	3	3	5	5	4	5	2	Not available	27
MARSAT	4	3	4	5	4	5	2?	2?	29
AEROSAT	4	2	4	5	4	5	3?	2?	29
Interferometry System 1	4	3	5	5	--	--	5	5	27
2	4	4	5	5	4	5	4	4	35
3	4	5	5	5	4	5	3	1	32
4	4	4	5	5	4	5	2	2	31
5	4	5	4	5	4	5	5	4	36

Scale:

5	Global	<100 m	<1 min	Feasible	3D	Feasible	Unlimited	<1 k
4	Global*	100 m-500 m	1-10 min	--	2D	--	1000-10000	1-5 k
3	Regional	500 m-2 km	10-30 min	--	--	--	500-1000	5-10 k
2	--	>2 km	>30 min	--	--	--	100-500	10-20 k
1	--	--	--	--	--	--	<100	>20 k

*Except for polar region.

6.0 PRELIMINARY ASSESSMENT OF USER INTERESTS AND INTERFEROMETRY APPLICATIONS

The major advantage or uniqueness of the interferometer system considered herein, lies in its ability to provide both a means for position determination and a cummunications capability to a large number of users engaged in a wide variety of activities. To bring the role that this integrated system might ultimately be expected to play into better perspective, and to identify more clearly the existing and possible requirements and applications of its potential users, a limited effort was undertaken to define these requirements and applications. This effort involved both a survey of the literature on past programs and studies, and a series of interviews with a small number of selected individuals in Government and industry*. It must be emphasized that this effort was limited, and that the information obtained and presented here is intended merely to be indicative of the possible requirements and applications of potential users and to provide some general guidelines for designers of future interferometer systems. Likewise, the numerical data presented here for system(s) capabilities and requirements were developed on the basis of the results of this limited survey and interview program and therefore cannot necessarily be considered truly representative of the needs of the potential user community. Any generalizations based on these data should be considered to possess only tentative validity.

Before presenting the requirements/applications expressed by the specific user groups identified in the survey and interviews, some of the requirements for general navigational accuracy, as established by the Department of Transportation in its National Plan for Navigation and some of the requirements promulgated by other Federal agencies concerned with or responsible for developing navigational programs, which should be considered in the development of the proposed interferometer system, are discussed briefly below.

6.1 General Navigation Considerations

The requirements for positional accuracy proposed by the Department of Transportation (DOT) in its National Plan for Navigation are $\approx$1 km (0.5 nm),

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* A list of individuals and organizations contacted is presented in the Appendix.

95 percent probability, throughout the Coastal Confluence Region (CCR); however, in some cases, accuracies of the order of about 200 m (0.1 nm) are specified. On the high seas, accuracies of the order of 2 to 4 km (1 to 2 nm) are required except in certain regions, such as the Gulf of Mexico, where an accuracy of approximately 500 m (1/4 nm) is required (DOT, 1972).

Although many studies have been conducted for the purpose of identifying user navigation requirements, no acceptable "clear-cut" means for arriving at definitive requirements has been developed. These studies do, however, present some reasonable guidelines.

The Office of Telecommunications Policy (OTP) designated the Department of Transportation as lead agency of the interagency committee on Navigation with the Departments of Defense and Commerce, and NASA as participants. The DOD coordinates its inter-Service navigation plans through the Defense Navigation Planning Group, sponsored by the Director of Defense Research and Engineering. The DOT maintains its National Plan for Navigation which is not concerned with DOD matters, but considers primarily Coast Guard-sponsored marine matters and trans-oceanic (long-range) aviation requirements. The Plan does not include maritime surveillance and navigation requirements of the maritime administration nor the DOT St. Lawrence Seaway Development Corporation. Neither does it deal with the growing experimentation in land-vehicle navigation of diverse agencies such as Urban Mass Transit Authority, the Department of Justice, the Energy Research and Development Administration, and the Federal Railroad Administration (CGA, 1974, p 267).

The OTP took steps to initiate the development of a national navigation program and to eliminate the apparent proliferation of navigation systems. The results of the OTP's first study are presented in Frenkel, et al. (1975). It is obvious from the results obtained in that study and other similar studies, that there is no universal navigation system at present that can satisfy the individual requirements of all users. Each system has its own advantages and limitations. The National Plan for Navigation should include the requirements of all Federal agencies, as well as the private sector for air, sea, and land users. The cost of navigation systems could be prohibitive. For example, the cost of the DOD-planned NAVSTAR/GPS could be several hundred million dollars. Therefore, Government planners for navigation should try to reconcile their differences in requirements in order to minimize overall system costs.

6.2 Overview of User Requirements and Interferometry Applications

Practically all functions or operations that require navigation data or positioning capability and communications information, in particular those relating to marine/maritime functions, can be served most effectively by the interferometer system considered here. These include functions that require navigation data for safety purposes; accurate position data for many types of surveys; position and communication data for search and rescue operations; disaster warning, monitoring, and traffic control; and all types of data collections and transfer. Most of these requirements can be satisfied with the interferometer system at its present level of technology.

The various user groups or functions considered in this analysis (excluding military functions) include:

(1) Shipping

(2) Fisheries

(3) Specialized operations

(4) Search and rescue and salvage

(5) Data collection and reporting

(6) Law enforcement

(7) Civil air.

It should be noted that major emphasis is given here to the first six activities (essentially for marine/maritime). The operations related to "Civil Air" are not dealt with in any detail since the interferometer system as presently conceived would have only very limited application. However, future technology interferometer systems, particularly those incorporating phased-array antennas for aircraft and high-speed moving vehicles, could satisfy many additional requirements including those of air traffic control and general aviation. It may be safe to say that such a system could then be competitive with the most sophisticated systems requiring the highest in positional accuracy and efficiency in operations.

A preliminary overview of the navigation requirements of the various users is presented in Table 6-1. The parameters representing user interest and requirements analyzed include horizontal positioning accuracy, position update interval, area of operation or coverage, and the number of users in each group. It should be noted that the numbers given in this table, in general, indicate the optimum or ideal with respect to what a particular user would "like to have". These numbers, therefore, are subject to change, particularly if the user were offered alternatives. For example, a user might relax his requirement for update interval from, say 5 seconds to 30 seconds or more, if this would afford him a significant cost saving and perhaps, as a result, permit him other capabilities or tradeoffs. For this reason, a range of numbers has been given.

Table 6-2 summarizes the capabilities of the five "strawman" interferometer systems and correlates them with various user applications. Detailed information on these systems is presented in Section 4. In Table 6-2 the "Interferometer User Application" areas for each of the systems are categorized according to the position update interval requirement. The principal reason for this classification is the limitation that the frequency of update interval imposes on the potential number of users that can be accommodated by each system. This user limitation is dictated by the number of channels available for each system, and the user mix depends on the individual update requirements. Usually, the category for continuous update (Column 2) is the upper limit. For example, if 1000 channels are available and all are used for continuous updating (5-second interval), 1000 users can be accommodated; however, if one-half of the channels are used for continuous updating and one-half for 10-minute updating, over 50,000 users can be accommodated. Five-second interval was considered continuous for Systems 1, 2, 3, and 5 while 10 seconds was considered continuous for System 4.

6.2.1 Shipping

Table 6-2 shows that the requirements of many users in the shipping industry can be met by the interferometer system. The biggest application would be for ship navigation on the high seas for which the low-accuracy navigation capability of System 2 would be adequate. At up-date intervals of 10 to 30 minutes

TABLE 6-1. PRELIMINARY OVERVIEW OF NAVIGATION USER REQUIREMENTS

User/Function \ Requirements	Horizontal Positioning Accuracy	Update Interval	Coverage	No. of Users	Comments
SHIPPING					
High Seas	200m-2km	10-30 min	Global	<10,000	Telex
Intercoastal/Harbor Approach	50m-1km	<1 min	Coastal	<10,000	Voice of interest
Tankers, Icebreakers	200m-2km	10 min-1 hr	Global	< 1,000	Voice desired, Telex required
Recreation	1km-3km	>10 min	Coastal	>10,000	
FISHERIES					
Research	25m-200m	10 sec-1 min	Global	<100	Weather forecast, etc.
Mid-Water Trawl, Purse Seine	150m-1km	<1 min	Regional		
Bottom Trawl, Pots, Etc	25m-100m	10 sec-30 sec	Coastal	<10,000	
High Seas	250m-1km	1-10 min	Global		Wave height and weather for spotting procedure
SPECIALIZED OPERATIONS					
Hydrographic Charting	25m-1km	10 sec-30 sec	Global	<300	
Marine Boundaries	10m	5 sec	Global	<100	
Test & Calibration	<10m	Continuous	Regional		
Research Vessels	25m-1km	10 sec-1 min	Global	<300	Telex/facsimile of interest
Geophysical Exploration	<10m	10-30 sec	Global/Regional	<100	Wind/wave heights, Telex/ facsimile required
Mineral Surveys	25m-500m	10 sec-1 min	Global	<100	
Placement of Platforms, Buoy, Equipment	10m-50m	<1 min	Global	<100	
Pipeline & Cable Laying	10m-100m	<1 min	Coastal/Regional	<100	Voice of interest
SEARCH & RESCUE & SALVAGE	1km-10km	1-10 min	Global/Regional	<100	
DATA COLLECTION FROM PLATFORMS, BUOYS, BALLOONS, SHIPS	2km-5km	1-2 hrs	Global	>10,000	
LAW ENFORCEMENT					
Fisheries	1km	1-2 hr	Regional/Global	<1,500	Voice communication desired
Drugs	50m-1km	1 min-1 hr	Global	<100	
CIVIL AIR					
Enroute Over Land	200m-1km	<1 min	Regional	>100,000	
Enroute Over Oceans	200m-1km	<10 min	Global	<10,000	

TABLE 6-2. SUMMARY OF STRAWMAN INTERFEROMETER SYSTEM CAPABILITIES VS. USER APPLICATIONS

Capabilities \ Applications	User Applications: Update Interval: Continuous 5-10 sec	Update Interval: 1 min	Update Interval: 10 min	Update Interval: 30 min
SYSTEM 1 (Surveillance & Data Collection) Accuracy: 1-2 km Data Rate: < 30 bps No. Channels: ≈ Unlimited User Cost < $ 1K	No. of Users: ≈ Unlimited Drug Law Enforcement (Fast Vehicles), SAR Data Collection, Platforms, ELT (Ships & Aircraft)	No. of Users: ≈ Unlimited Same	No. of Users: ≈ Unlimited Same + Drug Law Enforcement (Low-Speed Craft) Data Collection: Buoys, Balloons	No. of Users: ≈ Unlimited Fisheries Law Enforcement Data Collections (Same)
SYSTEM 2 (Navigation/Surveillance/Data Transfer) Accuracy: 125-500 m Data Rate: < 100 bps No. of Channels: 1000 User Cost: $5-10K	No. of Users: <1000 Shipping: High Speed Craft Small Scale Charting Low Accuracy Oceanographic Surveys, Synoptic Data Collection Experiments	No. of Users: <10,000 Ice Breakers, Fisheries: Midwater Trawling, Shrimping, Tuna Intercoastal Shipping	No. of Users: <100,000 Merchant Marines: High Seas, Tankers, SAR, Tuna Intercoastal Shipping	No. of Users: <300,000 Same + Recreational Craft
SYSTEM 3 (Navigation/Surveillance/Data Transfer) Accuracy: 25-75 m Data Rate: 1000 bps No. of Channels: 500 User Cost: $25-50K	No. of Users: <500 Fisheries: Research, Bottom Trawl, Pots, Large Scale Hydrographic Charting, Geophysical Surveys, Placement of Equipment, Point-to-Point Data Transfer, Pipeline & Cable Laying	No. of Users: <5000 Shipping: Intercoastal/Harbor Oceanographic Surveys, Mineral Surveys, SAR	No. of Users: <50,000 Shipping: Intercoastal, Drug Law Enforcement: Cooperative Drill Ships	No. of Users: <150,000 Fixed or Semi-Fixed Platforms, Absolute Position of Drill Ships Land & Marine Geodetic Control for Unsurveyed Areas, Geodetic Control For Land Oil Exploration, etc.
SYSTEM 4 (Aerial Navigation/Traffic Control/Data Transfer Accuracy: 250 m Data Rate: <200 bps No. of Channels: 150 User Cost: $15-20K	No. of Users: <150 Supersonic Aircraft Except For Final Approach And Landing, SAR. (Limited by No. of Users and Lack of Voice Communications)	No. of Users: <2000 Airborne Survey Crafts, Ice Patrol, Great Lakes Shipping	No. of Users: NA If Phased Array Equipment is Developed for Aircraft Use, This Function of Air Traffic Control Could be Easily Accommodated Without Compromising the Number of Users.	No. of Users: NA
SYSTEM 5 (Navigation/Data Transfer/Surveillance, All Purpose System) Accuracy: 25 m-2 km Data Rate: 30-1000 bps No. of Channels: 1000 Low Bandwidth 1000 High Bandwidth User Cost: $1K-50K	Since This System is a Combination of System 1, 2, and 3, the User Will be a Combination of Those Listed Above for 1, 2, and 3.			

100,000 to 300,000 users could be accommodated which would present no difficulties for the system. Even at 1-minute interval, 10,000 users could be accommodated. Those requiring more frequent up-date intervals and greater accuracy would be operating near coastal areas, the Gulf of Mexico, in shipping lanes, and approaches to harbors. Primarily, System 3 or some combination of Systems 2 and 3 could satisfy their requirements. Ship traffic control in harbors and confluence regions and anticollision information could be accommodated by the interferometer system. It appears, however, that further analysis will be necessary to determine the number of channels required per given operation and the specific up-date intervals needed before final conclusions can be drawn. Present-day shippers are more aware of the importance of increased navigational accuracy for safety as well as for improved efficiency resulting from better planning, scheduling, and weather routing than they were only a few years ago. The additional inherent capability of data transfer of the interferometer would be welcomed by most shipping companies. The surveillance function may be of interest to large companies with many ships operating on a worldwide basis. Regulatory agencies such as the Coast Guard may have greater need for such requirements. Further exploration of Government agencies and industry's requirements is needed.

The projected user costs of the interferometer present no difficulty to the shipping industry. In fact, these costs appear to be competitive with their expenditures for systems presently employed. On the other hand, costs of equipment would be critical to the recreational boat users. No attempt has been made in this investigation to analyze in detail the requirements of the boating industry.

The total number of registered (Coast Guard registration required) U. S. vessels, as of January 1, 1973, was about 8,000,000. Of this number, only 54,436 were commercial ships of 5 tons or more. The remaining vessels were considered recreational crafts varying in size from small boats (less than 5 m) to about 20 m. The number of recreational boats over 20 m long was 2,691,173. It was estimated that a total of about 409,000 craft would be potential users of radio navigation systems. This estimate was given by F. J. Shafer (Director, Logistics and Communications Division, U. S. General Accounting Office) in his testimony before the House of Representatives Subcommittee on Coast Guard and Navigation, Committee on Merchant Marine and Fisheries (CGA, 1974, pp 263-285). Shafer also indicated that the Coast Guard is developing six traffic systems for several U. S. harbors for surveillance and control purposes at initial costs of $20 million for acquisition, $10 million for research and development, and annual operating costs in fiscal 1976 of over $4 million. In addition, the Coast Guard has identified vessel traffic system needs for 17 other U. S. ports.

The positional accuracy requirements for the shipping industry are summarized in Table 6-1. The highest accuracy required (about 50 to 200 m) is in the approaches to the harbors. The frequency of position update required is near continuous. The accuracy requirement decreases to about 1 km or more on the high seas. Similarly, the frequency of update also becomes less critical. In general, the accuracy and update requirements are also less critical for the relatively slow-moving ships such as tankers. Future hydrofoil and hovercraft will impose great demands on position accuracy and update intervals.

Interviews with shipping and tanker company personnel indicated that they have requirements for communications, particularly in sending telex messages concerning shipboard problems, diversion of tankers to other ports, relay of engine data, payroll data, etc. The greatest communications delays they have experienced are for areas in the Indian Ocean. They are interested in low-cost receivers, although, at present, some of them employ satellite navigation systems at an annual cost of about $100,000. Although surveillance could be of interest, they may have to conduct public relation campaigns so that ship captains do not feel that they are being watched. In any case, effective surveillance for collision avoidance requires that all ships have the necessary equipment. They have needs for weather routing, particularly for higher speed ships; however, some such services are already available to them.

6.2.2 Fisheries

The fishing industry has a need for high accuracy in positioning, especially for certain types of operations, to make them economically feasible. Fishermen, however, require inexpensive equipment that is simple to operate and reliable. Because of the relatively small size of their boats, the equipment should be compact.

It appears that most of the requirements of the fishing industry -- in terms of coverage, position accuracy, and equipment cost -- can be met by Interferometer System 2. The need for continuous position information may limit the number of users. Certainly, the update-interval tradeoff with other parameters needs to be considered as in shipping. Bottom trawling and lobster-pot location require greater accuracy than can be provided by System 2. However, these types of fishermen may not be willing to pay the higher cost of System 3 to achieve this accuracy. Therefore, additional analysis of their requirements and of the tradeoff between accuracy and cost should be carried out. Fisheries research which requires the highest accuracy could also be satisfied by System 3. Since most of such research is conducted either by large organizations or the Government, the equipment cost of System 3 may not be a limiting factor, and since most of the fisheries also have requirements for communication and data transfer, the cost of System 3 may be competitive with the cost of existing systems.

The U. S. fisheries represents a sizable industry in terms of economic value and potential user of improved navigation systems; for example, the commercial fisheries of the U. S. harvest about 5 billion pounds of fish per year worth over $800 million. About 70 percent of fish and fish products consumed each year in the U. S. are imported (about $1.5 billion worth). The largest of the U. S. fishing industries, in terms of dollars, is the shrimp industry followed by the tuna industry. Peru leads the nations in total volume, followed by Japan, the Soviet Union, China (Mainland), Norway, and the U. S. These six nations account for about 60 percent of the world catch (Thompson, 1971, and Murdock, 1975). The use of improved systems such as the interferometer could conceivably contribute to increased efficiency resulting in a greater share for the U. S. of the world catch.

As of January, 1973, the U. S. had about 19,350 commercial fishing vessels (CGA, 1974, p 271). The major navigation equipment used by commercial fisheries is LORAN-A. Many also have directional finders and some communication equipment. In the near future, many of the fishermen are expected to convert to the use of LORAN-C and/or the Omega system. These systems have been declared by the Department of Transportation, in its National Plan for Navigation, as the U. S. navigation systems to be employed in the Coastal Confluence Region and on the high seas, respectively. Most fishermen have been reluctant to invest more than a few thousand dollars in navigation equipment. In general, the position accuracy requirements vary from about 25 m to 1 km (see Table 6-1). Accuracies of about 25 to 200 m are required for research vessels, bottom trawl, pots, and long-line pots, and traps; accuracies of 150 m to 1 km are required for purse seine, high seas tuna fishing, mid-water trawl, and shrimping. With the exception of the high seas fishing, they have further need for near continuous positioning information (update intervals of 1 minute or less). According to Polhemus (CGA, 1974, p 152), "the commercial fisherman can show a direct economic correlation between navigation systems' performance and his profits-and-loss statement. Furthermore, he has the greatest need of all the users for accuracy, reliability, uninterrupted availability of signal and simplicity of operation and maintenance". The interviews conducted confirmed the importance of improved positional accuracy for the fishing industry in given areas. Many fishermen depend on past experience in particular areas to avoid hazards and, as a result, they often leave several square kilometers of potential fishing unexploited. Other requirements noted by the fisheries include the need for a system which, in addition to positional data, can provide a communication capability and information on temperature and ocean-wave heights (Murdock, 1975). Temperature is of particular interest, for example, to the albacore industry. Wave-height information can be correlated with local weather conditions and is useful for predicting local variations that often are not given in routine weather forecasts. In general, fishermen prefer passive navigation systems (active systems tend to reveal their locations to competitors) which are low cost but with a high degree of accuracy. Also, they are reluctant to accept any advanced system, particularly if they involve fairly complicated operations. Because of the relatively small size of their ships, they quite naturally prefer small-size equipment.

6.2.3 Specialized Operations

Specialized operations, such as hydrographic charting, determination of marine boundaries, geophysical exploration, mineral surveys, pipeline and cable laying, etc., require highly accurate navigation systems which can provide almost continuous position updating information with a good repeatability since it is essential that the ships and aircraft engaged in these activities be able to return to the precise location of previous operations or discoveries. Detailed discussions of these requirements can be found in several sources: Mourad, et al., 1968, 1972, 1974; Putzke, 1969, Cohen, 1969, Sheriff, 1973; Fubara and Mourad, 1973; Saxena, 1974; Marine Geodesy Symposia Proceedings, 1967, 1969, and 1974, NSIA, 1971. Interferometer System 3 appears to be the most suitable for these types of operations.

Because of the success of these operations depends on the accuracy of the navigation systems employed, these users often are willing to make substantial investments in them (present costs range between $200,000 and $1 million per ship). Although they represent only a small number of the users of navigation systems (less than 1500), they serve various functions and industries with gross sales volumes of several billion dollars annually. It has recently been estimated that during 1972-1973 the level of primary economic activity (or output) represented by the development of all U.S.-controlled ocean resources was about $7.5 to $7.8 billion (1973 dollars). This figure is expected to increase to about $23 to $26 billion by 1985 and $33 to $44 billion by the year 2000 (Magnuson, 1974).

By far the most stringent of the requirements are for those operations associated with the search for offshore oil and gas. The largest user of high-precision navigation systems is the geophysical exploration industry. Exploration for oil and gas has increased considerably in the offshore areas of the continental shelves and slopes. According to Savit (GSA, 1974, pp 292-296) a number of reasons have combined to produce this seaward drive, the most predominant of which is the apparent geological fact that most of the world's undiscovered oil and gas lie beneath the sea. Further, because drilling offshore exploratory oil wells is quite costly, the oil operator must have the best information possible to guide him to the places which appear to offer the greatest potential. In quest of such information, the geophysical exploration industry of the Free World operates about 80 vessels. These vessels are equipped with some of the best available navigation systems costing from approximately $0.25 to $1 million per ship. Their future positional accuracy requirements are for better than 10 m on a continuous updating basis or at intervals of 10 to 30 seconds. They are looking forward to satisfying such requirements by using the planned DOD NAVSTAR/GPS system. Placement accuracy of platforms, drill pipes, or other equipment is often required to within a few meters.

Interviews with several representatives of the geophysical and petroleum industries confirmed these requirements. In addition, these representatives indicated a need for a data-transfer capability (teletype messages, facsimile). Such a capability, in particular facsimile, is of interest to geophysical and surveying operators for communicating program changes and satellite weather pictures to their ships. It should also result in improved operational efficiency, maximizing profit margins by minimizing errors in present complicated methods of data relay (ship to base to ship). For geophysical and surveying operations near foreign land, the interferometer system would be attractive because it would eliminate dependence on shore installations of radio positioning systems. The surveillance/monitoring capability of Interferometer System 1 has potential for use by certain geophysical companies who own a number of ships operating on a global basis. Voice communication, although desired in some cases, is not a requirement.

The requirements for positional accuracy for mineral surveys and mining operations are somewhat less stringent since most of these operations are in the open ocean and cover large areas. Accuracy requirements of research vessels vary depending on the particular research problem being investigated. Those for which accuracy is least critical are general oceanographic operations, marine biology research, etc. The most critical requirements are for surveying operations and placement of equipment on the ocean bottom, submersible navigation, microbottom topographic mapping, etc.

Pipeline-laying operations are performed for the pipeline industry by specialized surveying companies that utilize the best available navigation systems. Present operations are being conducted within 200 km of the coast. These operations will extend further offshore in the future. Position accuracies of a few meters are required. Cable laying is done on a worldwide basis across the oceans. Accuracies of a few meters to 100 m are required. The accurate location of cables and pipelines is essential not only during the laying operation but, more important, for later recovery and repair purposes.

There is an ever-increasing demand for accurate and detailed maps in the deep ocean in support of various important activities such as economic development of resources, monitoring and preservation of the environment, commerce, national defense and a host of other efforts. Only about 10 percent of the ocean maps have acceptable accuracy (UN, 1970). Economic and scientific enterprises, search and recovery, and transportation interests require data over a wide range of map scales, from 1:2000 to 1:100,000. These activities require positional accuracies of better than 10 m for the large-scale maps and about 200 m for the small-scale maps. It should be noted also, that the accuracy requirements for horizontal positioning depend on the precision of sounding equipment (beamwidth and resolution) used in charting.

Perhaps the most critical requirements are those associated with the determination of marine boundaries and with the establishment and operation of marine test ranges for the calibration and evaluation of various types of equipment and systems.

6.2.4 Search/Rescue and Salvage

Search and rescue (SAR) operations require position information, communication/surveillance and coordination among several activities. The basic SAR steps include:

(1) Alarm signal from a craft in distress

(2) Receipt of signal by responsible organization and evaluation of its accuracy

(3) Location of distress craft

(4) Alert and dispatch information to nearby crafts

(5) Search

(6) Recovery

Operations over oceanic areas involve both aircraft and ships. Aircraft and surface vehicles are involved in overland operations.

All SAR functions could be served most effectively on a worldwide basis by the interferometer systems. Interferometer System 1 would involve the use of an inexpensive electronic location transmitter (ELT) device that could be activated either automatically or manually by the emergency craft. One of the three geostationary satellites (required for global coverage, between 70°N and 70°S) would receive the alarm signal instantly from ELT and promptly relay it to the coordinating center which would determine its position within an accuracy of 1 to 2 km. The coordinating center, which maintains surveillance (using System 1) of all ships and aircraft in the emergency area, would relay messages to those nearby ships or aircraft for immediate search and rescue. The coordinating center also determines whether further specialized SAR ships or aircraft should be dispatched to the emergency area. For these functions, any of Systems 2 through 5 might be used. Similarly, salvage operations could also be carried out efficiently through the use of one of these systems (2 through 5).

At present, many aircraft and ships, in time of emergency, employ Emergency Position Indicating Radio Beacons (EPIRB) such as the Emergency Location Transmitters (ELT), or the Distress Alerting and Location Systems (DALS). Other systems, such as the GRAN, are also being tried. These various systems send out alarm signals on certain frequencies that are received by nearby craft or various SAR organizations. These frequencies are also used for homing purposes during the search operations. In addition, the Coast Guard operates an Automated Merchant Vessel Emergency Reporting (AMVER) system, in which over 3000 ships from 60 different countries participate in reporting (once every 12 hours) their position, course, and speed to a computer/coordinating center. Thus, AMVER serves as a surveillance system which monitors the positions of all of these ships so that they may be called to respond to an emergency. One problem with this system is that the reporting by the ships is done only on a voluntary basis.

Perhaps the two basic SAR problems are:

(1) Monitoring and location of the craft in distress with sufficient accuracy to dispatch SAR craft

(2) Establishment of a common datum for both craft location and for the crafts executing the SAR operations.

At present, locating the distressed craft is based on the position it reports, which is often quite inaccurate. Coast Guard statistics for 1971 indicate that only 36 percent of the emergencies (46,334) provided sufficient position accuracy for effective SAR operations (Frankel, et al., 1975). It has been estimated that a satellite-aided SAR system could save about 400 lives annually (Baker, 1973).

If the average cost per life to the insurance companies were $250,000, this could result in total savings of about $100 million annually. The position accuracy may not be critical if the same type of navigation system is used by the craft reporting the emergency signal and by the craft or surface vehicles performing the search. Certainly the location accuracy plays a significant role in minimizing the time required for search and rescue. This will further result in smaller operational costs as well as saving more human lives by reducing the time they are exposed to various environmental hazards. The basic SAR requirements are:

(1) Effective system of coordination which includes surveillance and emergency craft location and communication between ships, aircraft, and surface vehicles

(2) Common reference system for reporting and for search

(3) Navigation accuracy of 1 to 3 km for emergency monitoring and better than 100 m for search and recovery.

Retrieval of objects from the ocean floor, whether in rescue operations or for salvage purposes, has basically the same stringent positioning requirements as SAR. Here, the position accuracy requirements are dictated not only by surface-position information needed by search ships but also by the needs of the submersible vehicles or the towed instrument maneuvering near the ocean floor. In addition, the resolution of scanning devices on the towed vehicles or submersibles also affect accuracy.

6.2.5 Data Collection

Data collection from remote areas and from sensors -- such as fixed or drifting buoys, platforms, and balloons -- is increasing in demand. The data often form the basis for establishing "ground truth" for satellite and other systems and for global models for the atmosphere, environment, ocean circulation, air-sea interface, weather forecasting, etc. Navigation requirements are for positioning and near-real-time tracking of the various sensors, interrogating them, receiving their data, and telemetering or relaying the data to a ground control center for processing and/or dissemination to various users. Examples of such data-collection systems are the National Data Buoy Program of NOAA (NDBP, 1970) the NASA experiments with the IRLS and the OPLE Systems (see Section 5.1.2.2). The type of data collected varies from one experiment to another but, in general, data on the following are included: surface and subsurface temperature, pressure, wind, humidity, wave heights, ice, underwater sound properties, pollution, salinity, bathythermograph, etc.

Interferometer System 1 appears best suited for data collection applications. If data transfer (two-way communication) is required, then either System 2, 3, or 5 is applicable.

6.2.6 Law Enforcement

The requirements of the law enforcement agencies for navigation and communication data vary depending on the nature of the operations.

The Law Enforcement Division (LED) of the NOAA National Marine Fisheries Service, along with the Coast Guard, has responsibility for monitoring the locations of some 1500 U. S. vessels and many more international fishing vessels, and the enforcement of the law. For example, there are many species of marine life that are protected by law such as stone crab, deep sea red crab, green conch, surf clam, grass sponge, and yellow sponge. Also, the American lobster on the Continental Shelf is protected by law from foreign vessels. Consequently, the National Marine Fisheries Service broadcast the location of the lobster pots twice each day. The Yellowfin Tuna Agreement specifies fishing rights by area and month. The tuna area boundaries are specified to within 5 km unless they can be accurately defined. At present, NOAA has five regional centers associated with the monitoring of fishery operations and enforcement of the laws. These centers are located in Alaska, Washington, California, Florida, and Massachusetts.

LED, in its monitoring role, has the following navigation and communications requirements: (1) an inexpensive ($1000 to $1500) self-contained system that can be placed on ships for location monitoring at intervals of 1 to 2 hours, (2) communication/data relay, and (3) receiving an SOS signal in times of emergency. The number of vessels involved is about 1500 (U. S.). The monitoring responsibility could be shared by the five regional centers. Interferometer System 1, which is low cost and can accommodate an unlimited number of users, could be used.

The Drug Enforcement Administration (DEA) is concerned with the monitoring of drug traffic and law enforcement on a worldwide basis. This involves tracking of all types of suspected vehicles and craft (on land, on the ocean, or in the air), both cooperative and noncooperative. The position accuracy and update interval required vary depending on the speed of the target. For example, for fast-moving targets such as automobiles positional accuracy of about 50 m at 1-minute intervals is required, and for ships 1 to 5 km at 1-hour intervals. DEA has several regional centers and often cooperates with local authorities in the pursuit of suspected vehicles. The total number of ships or aircraft involved at any one given time is about 6 to 12 and seldom exceeds 24. In the pursuit of land vehicles, the position coordinates must be converted in real time to local street numbers. Low power output and small-size equipment are essential for noncooperative targets. For cooperative targets 100 watts of power is acceptable. Voice communication and teletype messages are of interest to DEA but are not required.

Since DEA requirements include navigation and surveillance for many types of vehicles and craft (both slow and fast moving) and a communication capability as well, all five interferometer systems would be applicable.

6.2.7 Civil Air

A multitude of functions are performed by civilian aircraft including position determination, traffic control, collision avoidance, search and rescue, passenger telephone, and weather advisory. In most cases position-fixing information is required; collision avoidance requires position fixing and quick-reaction ground control. The remainder of the functions rely on communication (Weihe, 1968; Leavy, 1968). The requirements vary with the type of aircraft used (subsonic, supersonic, general aviation, specialized, etc.), the function served, and the airspace (over ocean, over land, terminal, etc.). Since the present interferometer system concept has only limited application to air traffic control, the civil air requirements will not be discussed here in detail. Some of the applications are shown in Table 6-2 under System 4. The small number of channels available (150) results from limitations on the aircraft antenna. Design of mechanically steerable antenna is too complex to be practical. It is possible, however, to design a phased-array antenna that could alleviate these problems and permit an increase in the number of users. For a comprehensive discussion of civil air requirements the reader should refer to Frankel, et al. (1975).

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APPENDIX

LIST OF INTERVIEWS

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LIST OF INTERVIEWS

(1) Trunkline Gas Company, Houston, Texas - Messrs, J. W. McAnneny, J. L. Deavenport, and M. Schism.

(2) Brown & Root Inc., Houston, Texas - Dr. J. B. Weidler.

(3) Seiscom Delta Inc., Houston, Texas - Dr. R. E. Sheriff & Mr. F. Bodner.

(4) Western Geophysical Company, Houston, Texas - Messrs, D. G. Shave and M. Evans.

(5) LORAC Service Corp., Houston, Texas - Mr. M. H. Curlin.

(6) Chevron Petroleum International, San Francisco, Calif. - Mr. D. Quam.

(7) Chevron Shipping Company, San Francisco, Calif. - Mr. D. E. Appleton.

(8) Standard Oil Company of Calif., San Francisco, Calif. - Mr. J. W. Earhart.

(9) American President Lines, San Francisco, Calif. - Mr. L. A. Harlander.

(10) Pacific Steam Ship Inc., San Francisco, Calif. - Mr. R. Abbott.

(11) Woods Hole Oceanographic Institution, Woods Hole, Mass. - Dr. J. R. Heirtzler.

(12) Drug Enforcement Administration, Washington, D. C. - Messrs, G. Carp, S. L. Green, and J. J. Sugrue, Jr.

(13) Goddard Space Flight Center, Greenbelt, Md. - Messrs, W. C. Isley, D. L. Endres, I. Gallicinao, W. Allen, and L. J. Roach.

(14) IBM, Gaithersburg, Md. - Mr. J. Heinrich

(15) National Marine Fisheries Service/Law Enforcement Div. of NOAA, Washington, D.C. - Messrs, M. M. Pallozi and W. P. Allen.

(16) National Marine Fisheries Service/Financial Assistance Div. of NOAA, Washington, D. C. - Mr. J. Murdock.

(17) National Marine Fisheries Service of NOAA, Rockville, Md. - Mr. M. R. Greenwood.

(18) Environmental Data Service of NOAA, Washington, D. C. - Dr. T. Austin.

(19) NOAA Fleet Operations, Rockville, Md. - R. Admiral E. Taylor.

(20) NOAA Corps, Rockville, Md. - Admiral H. D. Nygren and Dr. M. G. Johnson.

(21) Defense Mapping Agency, Washington, D. C. - Col. L. D. Beers.

(22) Naval Research Laboratories, Washington, D. C. - Mr. L. L. Cunningham.